MECHANISMS FOR FACILITATING A VITAL AND DYNAMIC EDUCATION SYSTEM: FUNDAMENTAL ROLES FOR EDUCATION SCIENCE AND TECHNOLOGY

by

Roy D. Pea and Elliot Soloway
Cognitive Systems, Inc.

October 31, 1987

This document was prepared under a contract with the Office of Technology Assessment, Congress of the United States, for the assessment, *Power On: New Tools for Teaching and Learning*. The conclusions are those of the authors. The document does not necessarily reflect the analytical findings of OTA, the Advisory Panel, or the Technology Assessment Board.

J952-35.

Table of Contents

Executive Summary 1
Preface 4
1. Introduction: Bridging the Gaps 7
    1.1. Roles for Research and Development for Bettering Education Through Technologies 9
    1.2. The Complexities of Education Require Scientific Understanding to Guide Practice 11
    1.3. Computers are Different Than Any Previous Educational Invention 12
2. Cognitive, Social, and Instructional Aspects of the Education Sciences 14
    2.1. View of the Nature of the Learner 14
    2.2. View of the Nature of "Understanding" 16
    2.3. View of Materials Needed for Learning 19
    2.4. View of What Pedagogical Tasks and Strategies are Effective and Why 23
    2.5. View of the Role of the Social Context in Learning with Technologies 25
3. What Specific Research and Technology Directions Could Bridge the Gaps? 27
    3.1. Advancing the Educational Technology Available to Schools 30
    3.2. Emerging Computing Standards for Undergraduate Educational Technology 33
    3.3. Theory-based Educational Technology Research and Development Strategy 34
    3.4. Changing What Students Do 35
        3.4.1. Intelligence Extenders 37
        3.4.2. Microworlds: Context-Based Learning 42
        3.4.3. "Intelligent" Tutors and Coaches 44
        3.4.4. Networking 49
        3.4.5. Multimedia Learning Environments 51
    3.5. Changing How We Track Learning 58
    3.6. Changing What's Taught 60
    3.7. Changing What Teachers Do 65
    3.8. Changing the Schooling Environment 67
    3.9. Other Needed Research and Development Activities 69
4. Policy Suggestions: Plans for Revitalizing American Education 72
    4.1. Option 1: Significant Increase in Federal Spending 75

  - 4.2. Option 2: Modest Increase in Federal Spending......................89
  - 4.3. Option 3: No Increase in Federal Spending................................91

5. References..93

6. Appendix A: Structured Interview Guideline Distributed to Respondents..122

7. Appendix B: Major Institutions and Laboratories..................................125

8. Appendix C: Examples of Education Science and Technology Projects..126

Executive Summary

This report was prepared as one component of an OTA project entitled "Educational Technology: An Assessment of Practice and Potential," requested by the U.S. House Committee on Education and Labor. The objectives of our particular project were: (1) synthesize current activities and directions of research in education science (the cognitive, social and instructional sciences), and (2) characterize how opportunities brought about by theoretical advances in education science and developments in multimedia, interactive, information processing technologies can be brought profitably and effectively to bear on American education.

There is an ever widening gap between the school and rest of society: what students do in school makes less and less contact with what is required of them to function as productive citizens in a participatory democracy. The key to bridging that gap lies in revitalizing the educational process. A cornerstone in that effort can be education science. In particular, research in the cognitive, social, instructional, and computational sciences has brought about a fundamental change in our thinking about learning and teaching. In particular, there has been a paradigm shift from viewing education from a curriculum/subject matter perspective to viewing education from a learner and teacher perspective. Rather than students having to adapt to a given curriculum, we can now draw on our fine-grained theories of how students actually go about learning to adapt the curriculum to the student. Moreover, advances in information processing technologies enable these new insights into learning and teaching to be embodied in qualitatively different sorts of educational products: computer-based microworlds, where, through the medium of high-quality, color graphic simulations, students can explore the inner workings of the living cell, or design and test mini mechanical robots; intelligent tutoring systems, capable of providing true one-on-one instruction in subjects such as geometry and algebra.

We present a framework, consisting of the following categories, for organizing the R&D directions considered most promising by experts in the field: (1) changing what students do; (2) changing how we track learning; (3) changing what's taught; (4) changing what teachers do; and (5) changing the schooling environment. In each category, we first discuss the theoretical justification that supports the changed view. Then, we identify specific technological innovations embodying the theoretical principles that create promising new learning and teaching environments.

Our analyses suggest that there are many reasons why it has been difficult to transfer advances in the scientific understanding about educational processes and the prototype technologies influenced by them to educational practice. Several major reasons for these difficulties have been: funding primarily from military or business contracts that has focused efforts on relatively narrow, training issues; unstable and insufficient funding resources in fundamental education science at the precollege level; inadequate coordination of R&D efforts with the teaching profession and other educational organizations, as well as commercial technology developers and professional publishers.

A range of mechanisms are needed in order to bring about the major changes that are envisioned for education through education science and the innovative use of technology. We outline three options for a Federal role in supporting the development and nurturing of such mechanisms: from a significant increase in support, to a modest increase, to no increase. Moreover, we assess these three options with respect to their potential for developing mechanisms that can achieve goals such as: providing a base for the development and exploration of new ideas and technologies in education science, developing a community infrastructure, providing for the integration of classroom teachers into all phases of the research and development process, and providing links to the commercial sector in order to effectively produce and disseminate quality technological products.

A cornerstone of the first two options is our call for Centers of Interactive Technology and Education (CITEs). A CITE is an interdisciplinary, educational science and technology research and development center, that will also serve to coordinate significant activities in graduate, professional, and educator training, and educational technology product development. CITEs would operate with core federal support, with significant contributions from corporate, foundations, state and local institutional sponsors. The cost of 1 CITE for a year will be about $10 million. Fully a third of this will go for "in practice" activities: supporting an associated school, supporting teacher education, etc. The types of CITE activities proposed, as well as staff levels and composition, reflect theory-practice integration by design, as well as the belief that education science and technology is fundamentally an engineering and not a pure science.

The magnitude of the problems facing us in education is large. In order to make an effective dent, we need to commit ourselves to a substantial program of research and development. Education science coupled with innovative uses of technology has an unparalleled potential for meeting the challenges. With sufficient Federal support, that potential can be actualized.

Preface

This study stands on the shoulders of many others. We are especially grateful for the ideas and insights provided by our colleagues listed below, who responded to our interview guideline and related queries under severe time constraints, either through face-to-face conversations, electronic mail, telephone, or writing. Their contributions to the report are innumerable, and they provided a depth to our analyses that would have not been possible without their help. In most cases, they also greatly aided us by providing references to recent reports of research and development projects:

Alfred Bork, University of California, Irvine
Barbara Bowen, Apple Computer, Inc.
John Bransford, Vanderbilt University
John Seeley Brown, Xerox Palo Alto Research Center
Jerome Bruner, New School for Social Research
Victor Bunderson, Educational Testing Service
Richard Burton, Xerox Palo Alto Research Center
Susan Carey, MIT and Harvard University Educational Technology Center
John Carroll, IBM Watson Research Laboratories
William Clancey, Stanford University
Allan Collins, Bolt Beranek and Newman
Suzanne Damarin, Ohio State University
Andrea DiSessa, University of California, Berkeley
Marshall Farr, Consultant in Cognitive and Instructional Sciences
Dexter Fletcher, Institute for Defense Analysis
Robert Glaser, University of Pittsburgh
James Greeno, Stanford University
Mitch Kapor, Lotus Corporation
Alan Kay, Apple Computer, Inc.
Midian Kurland, Bank Street Media Group
Jill Larkin, Carnegie-Mellon University
Alan Lesgold, University of Pittsburgh
James Levin, University of Illinois, Urbana-Champaign
Norman Meyrowitz, Brown University
Alan Newell, Carnegie-Mellon University
Raymond Nickerson, Bolt Beranek and Newman

Ernest Rothkopf, Teachers College, Columbia University
Roger Schank, Yale University
Judah Schwartz, Harvard University Educational Technology Center and MIT
Karen Sheingold, Bank Street College of Education
Kurt VanLehn, Carnegie-Mellon University
Nichole Yankelovich, Brown University

We wish to also acknowledge the help of many other individuals who provided related documents and information for our project: Susan Chipman, Office of Naval Research; John Cole, Library of Congress, Center for The Book; Robert Cavalier and Kenneth Friend, InterUniversity Consortium for Educational Computing, Carnegie-Mellon University; Lawrence Frase, Bell Laboratories; Sarah Kiesler, Carnegie-Mellon University; Marcia Linn, University of California, Berkeley; Arthur Melmed, New York University; Joseph Psotka, Army Research Institute; Senta Raizen, National Research Council of the National Academy of Sciences, and Richard Ruopp, Bank Street College of Education.

A number of others that we contacted were out-of-touch during the period when were preparing our report, or were otherwise unable to respond to our inquiries on such short notice. In the case of all those individuals listed below, we therefore read recent summary or empirical reports from their laboratories or projects, and incorporated references to their work and viewpoints insofar as possible in the report. We wish to acknowledge these individuals in that capacity: Ann Brown, University of Illinois, Urbana-Champaign; John R. Anderson, Carnegie-Mellon University; Michael Cole, University of California, San Diego; Wallace Feurzeig, Bolt Beranek & Newman; Thomas Landauer, Bell Communications Research; Nicholas Negroponte, MIT; Donald Norman, University of California, San Diego; Seymour Papert, MIT; Robert Sternberg, Yale University; Albert Stevens, Bolt Beranek & Newman; and Patrick Suppes, Stanford University.

In our report we have aimed to synthesize these various discussions, correspondences, and readings-- in terms of a novel framework we developed for purposes of this report to characterize advances in the field of education science and technology, and in our substantive and policy analyses of corresponding directions and institutional arrangements for promoting significant R&D. We have also built wherever possible on the details and conclusions from previous major reports over the past five years (25, 50, 112, 113, 120, 121). Our questions to our respondents (see Appendix A) elicited specific points enabling us to flesh out this conceptual framework with concrete details of current project directions and experts' judgements concerning priorities for the field. As we expected, given that the guideline was developed to cover a broad range of topics for a diverse range of experts, not all experts provided responses to all questions, choosing quite reasonably to focus on topics for which they considered themselves specialists. It is important to note that what we provide in this document is thus a qualitative synthesis of these responses; the interview guideline was not designed as a quantitative research instrument.

There was a buzz of excitement among our respondents, and a widespread sense of the recent birth of an intellectual infrastructure for a new community. We found this vitality inspiring, and hope that our report captures some of that enthusiasm and energy.

1. Introduction: Bridging the Gaps

There are ever-widening gaps between schools and society. Our report highlights three such gaps. These gaps are detrimental not only for the economy of our nation, but for future prospects of enlightened citizens as the foundation and beneficiaries of a participatory democracy. In particular, there are substantial gaps between the knowledge students are capable of using after formal schooling and the knowledge they need to participate effectively as productive citizens in a democracy; and between the tools for learning and problem-solving utilized in society and those involved in the nation's educational activities. The final gap--whose narrowing with technologies holds promise for narrowing the other gaps--is between research knowledge of learning as a cognitive, socially situated process, and educational practices primarily dependent on "transmitting" information or procedural skills for manipulating symbols.

Widespread attention has been devoted to documenting the ills of present American education. This state is described in several dozen reports from book-length reports and special commissions appointed by governmental, business, and research agencies (6, 17, 34, 50, 77, 79, 93, 100a, 115, 129a, 148c, 153, 173, 174). We know that illiteracy is widespread, that education in mathematics, science, and technology is not sufficient, that understanding of culture, humanities, social affairs, and history is impoverished. Participation in science and mathematics education is decreasing, yet it is key to the nation's technological vitality in an increasingly competitive world economy (57, 64, 86, 116, 120, 131, 131a, 180, 187), and particularly underrepresented by women and minorities (1a, 43, 50, 120, 178). Employers find too few high-school and even college graduates prepared in the basic educational competencies needed to function effectively in organizations (127a, 144a, 185b). These are not just vocational concerns, but issues of deep educational significance and effective development of human resources.

The knowledge gap. The problem of students' knowledge utilization, also described as "transfer," is a serious underachievement of much present education. Research and findings from the National Assessment of Educational Progress and other sources indicate that students have difficulties in reasoning and problem-solving where they must put what has been learned in school to use in writing, scientific and mathematical reasoning, critical thinking about complex issues facing society, and other real activities (36, 77, 130, 153). Proposals to orient teaching and learning so that it is "situated" in contexts of application rather than as isolated general skill-training or fact-memorization may help ameliorate this condition (95, 127a, 147, 185a). And schools as yet have placed far too little emphasis on the inquiry skills required to make effective use of vast information databases, much less the knowledge integration and communication skills needed to make use of the information acquired through such search (15, 49, 86, 145).

The technology gap. As this report will document, very rapid changes are taking place in the mass market computer-based technologies used to support learning, problem-solving, and entertainment activities in society, both in the workplace and in homes. Market trends and projections, as well as research, suggest that the gap has widened and will, given today's directions, continue to widen between societal and school-based educational uses of technologies (11, 64, 65, 116a, 186). This is not important strictly because of the prevalence of technologies in society, but because the ones that are in use are commonly empowering humans in helping them to better reason, learn, communicate, and collaborate (136, 138). And students are largely not getting access to these advantages. Optimistic popular reports citing statistics on the growing numbers of computers in schools are deceptive, since they include substantial quantities of primitive equipment with only marginal educational uses--typically for "computer literacy" or low-level computer programming with no future application.

The research-application gap. Although a broad consensus has emerged about needed changes in educational practices from the cognitive, social, and instructional sciences--what we henceforth call in shorthand *"the education sciences"*--there have been few changes that have taken place in the state of the nation's education as a result. While the research-practice link has always been problematic, these research communities have begun to engage in a new paradigm of work, involving educational practitioners and real educational settings in research and development activities, that holds great promise for narrowing this traditional gap (26, 50, 58, 65a, 82, 116, 116a, 128, 162).

Possible relations between the knowledge and technology gaps. As we will show, concerted federal efforts are required to "yoke" societal uses of technology that are human-centered to educational uses of technology. This process, designed so as to narrow both the knowledge and the technology gaps, should be guided by the best research the cognitive, social, and instructional sciences has to offer for how processes of learning for understanding take place, and for how people are better enabled to realize their creative and productive potentials, and to lead fulfilling lives.

1.1. Roles for Research and Development for Bettering Education Through Technologies

Research in the cognitive, social, and instructional sciences, and the accompanying use of theory-guided educational technologies, could do much to narrow these gaps.

The strategy to be pursued should whenever possible involve the application of such sciences to the design, development, and use of technologies in education that are *human-centered*, not technology-centered (136). The reason for these provisions is that there is no reason to believe that the uses of technology *per se* will improve education. As artefacts, computers neither teach nor intrinsically carry good, but serve as implements of imagination (or its absence).

Indeed, technology as often as not can cause as many problems as it solves (5). And although we believe there are important reasons for keeping pace with technology developments in society, it would be foolhardy to make education technology "driven," rather than critically responsive to educational potentials of new technologies. As in the case of computers in complex organizations (101), many planful, purposive, and effortful acts beyond the technology--how it is designed, thought about, used, supported, how it is integrated with other activities and tools of teaching and learning--are integral to its effectiveness as catalyst of human development and educational attainments (26, 42, 50, 70, 148). Where research-guidance from these human sciences can be expected to make a positive difference in the educational tools provided and used, it should be exploited. And as we shall see, various incentive structures could improve the utilization of research and development results for technologies in educational settings.

It is essential to keep examining whether computer technologies can, as many theorists and researchers conjecture, dramatically improve the processes of teaching and learning (16, 19, 20, 24, 26, 28, 42, 51, 52, 110, 144, 145, 166). Several indications support this belief, even though the features and uses of many educational technologies fall seriously short of what will be required for such changes to occur. Many of the advances in understanding the nature of thinking and learning in the cognitive sciences have been dependent upon the use of the computer as a device for explicitly modelling or revealing mental processes (25, 66, 73, 81, 84). The methods and tools emerging from this research, now exploited commercially in artificial intelligence and in cognitive tools, can be brought to serve the processes of education. The symbol storage and manipulation capabilities of computers used in this research have also served society in allowing for the creation of powerful cognitive tools, such as writing systems, graphics and animation programs, relational databases, project planning and management tools, and expert systems (13, 95a, 136). Many of these tools act as imagination and intelligence "extenders," serving to make new kinds of reasoning, prediction, understanding, cooperation, and creative expression possible (119, 136, 138, 139, 146, 148, 181, 190, 202). The ability to provide mind-like artefacts in educational processes such as intelligent tutors, intelligent help for learning to use tools, and "interactive" books may also prove important.

1.2. The Complexities of Education Require Scientific Understanding to Guide Practice

We are in a new era of science on processes of education. Those who examine the science of learning and the detailed practices of effective instruction have come to appreciate the much, much greater complexity of education than heretofore recognized (e.g., 116, 120). The society at large must come to appreciate the extraordinary complexity of what we ask people to master in education. Otherwise, patchwork solutions like "longer school days," without more fundamental analyses of cognitive, social, and instructional aspects of learning, will continue to be proposed and implemented with marginal effects.

To effectively guide the practices of education, the development of educational technologies including curricula and computer tools, and the education of teachers for promoting student learning, we need a deep scientific understanding of how minds in society learn.

The research community commonly compares our scientific understanding of mind in education today to our understanding of body and medicine in the early 1800's. Folk theories of medicine predominated then, and folk practices in education largely predominate today. Just as the everyday citizen feels expert in judging what is wrong with education, and how to do it better, so the everyday citizen felt expert in the 1800's in diagnosing and treating the body's ills. Everyone had elixirs and cures. The everyday citizen was wrong then, and except for some areas of learning that can be informally acquired outside formal schooling, that citizen is largely wrong about education today. What transformed medical practice was medical science, requiring the best minds in highly-focused empirical attacks on the nature of disease and biological systems, and use of the most advanced technologies available, tuned specifically to the problems' dimensions.

Understanding the workings of mind in learning in society is one of the major frontiers of science. Until the complexities of education are better appreciated, we cannot expect popular enthusiasm about research and development for educational technologies. We cannot expect substantive funding at the high levels required to achieve a sufficient scientific understanding of how the mind works in education, or to attract the best minds to improving education (120). Instead, we may see continuation of past funding efforts, perceived by the education science community as largely sporadic, short-term, and isolated in nature. This problem is further borne out by the astonishing fact that federal support for research in education has expenditures of one-tenth of one percent of the education budget, in contrast to 20 times that figure for the health budget, and 150 times that figure for the defense budget (116). Education will go on suffering with such inattention. Yet we cannot continue to practice folk medicine with student's minds.

1.3. Computers are Different Than Any Previous Educational Invention

We all know about the information revolution, and the computer's role as a "once in a century" innovation (172a). It has served to kindle fundamental rethinking of the nature of education, for three major reasons. First and foremost it has provided the microscope for new conceptions of mind--how it works in reasoning and learning. Secondly, since it is a "metamedium" for information creation, storage, transformation, and communication, it has become a universal multimedia instrument for education. And thirdly, in the prosthetic powers it provides for scaffolding mental activities and managing information complexity, it has opened doors on human potential and possibilities that have fired the imaginations of educators around the world.

These are great reasons for hope. But they come with great costs of realization, since they make clear that we are no longer in a period of education "business as usual," but a new technological era. What have we come to see about education, in part through the arrival of information technologies? What kinds of insights and new levers might the humane use of computers offer?

Computers have within a short decade of use in mass society placed in great relief the plights of education. Of course there have been other contributions to these recognitions. But through their use as simulation tools for constructing cognitive science theories of mind, we have begun to see, in a manner not at all apparent in the neo-behaviorist theories of learning in decades past, how poorly education achieves the aims of sound reasoning in its rich varieties, of adequate comprehension and communication of ideas and images, of invention and creativity, of lifelong learning and a fulfilling existence.

2. Cognitive, Social, and Instructional Aspects of the Education Sciences

We will focus here on the changes that have taken shape in the scientific understanding of education, and the repercussion they have for every facet of its conception and practices. While frontier studies in this field debate the particular details of how knowledge is mentally represented, and the processes and mechanisms involved in conceptual change and acquisition of problem-solving strategies, it is nonetheless generally agreed that the consensus directions highlight the necessity of substantial reforms in educational practices and in the very idea of "education." We will characterize changes in consensus views on:

-- The nature of the learner

-- The nature of "understanding"

-- What materials are needed for learning

-- What pedagogical tasks and strategies are effective and why

-- Roles of the social context in learning with technologies

2.1. View of the Nature of the Learner

A new consensus view of the learner, incongruent with most present-day practices, characterizes present research in the education sciences. Research concludes that the dominant *transmission* view of knowledge is deeply misguided (reviewed in 23, 80, 102). According to this view, the major pedagogical activity is to provide well-structured presentations of material to be learned, primarily through lecture, demonstration, and recitation (124). Instead, we now see that new learning is *constructed* in terms of prior knowledge by an active learner in a social context, that knowledge is best acquired in functional contexts with similarities to situations for future knowledge transfer, and that learners need to learn strategies and methods for autonomous "repair" of understanding when applications of prior knowledge to a novel situation fails.

The new view of the learner, influenced by the work of Piaget (148b), Ausubel (7), Bruner (26a) and others in the 1960's and 1970's (38, 80,184), sees the development of intelligence generally, and of subject-matter understanding in education in particular, as actively constructed by the individual (e.g., 152). New knowledge is acquired in relation to previous knowledge, building upon intuitive, informal experiences. Such "experiential knowledge" must be reckoned with in education. Much recent research involves "diagnosing" the understandings, preconceptions, and interests that learners bring to formal instruction, so that instruction may bridge experiential and formal, school-based learning. Such bridging is important because severe limits arise in the kinds of problems these informal reasoning methods can solve. Analyses of preconceptions have been particularly revealing for topics in science (32, 33, 39, 40, 48, 58, 60, 61, 88, 106, 122, 123, 140, 142, 193, 194, 201), mathematics (21, 29, 35, 75, 100, 154, 155, 168), and programming (14a, 95b,101a, 148a, 177, 177a). Research work in the development of reading (6, 10, 133, 143) and writing skills (12, 26, 58a) also reveals the importance of helping students build upon a rich set of communicative strategies, techniques, and experiential topics derived from oral language use that makes sense to them.

An understanding of subject matter so that problems can be solved or creatively posed requires a richly interconnected network of concepts, principles, and skills (41, 76, 81, 84, 107). The necessity of subject matter knowledge in expertise has been recognized for centuries. What is new is the research-based recognition that it is *not* a knowledge base of facts per se that should be an instructional goal. Instead, students need to acquire facts, principles, or theories as *conceptual tools* for reasoning and problem solving that they can see makes sense because they have consequences in meaningful contexts (18, 26, 50, 185a). The knowledge base acquired through education should not be inert, memorized for recall on tests, but active, conditionalized for application to appropriate contexts of use (77). The new educational awareness of the pedagogical priority of facts-in-use has led to an increasing emphasis on what have been described as "guided microworlds," "appenticeship learning, or "learning by doing" (52, 65a, 95, 153). In such methods, students acquire knowledge-in-use, experiencing and employing new ideas in contexts of application with many similarities to their desired contexts of transfer.

Learners, even expert learners, routinely face novel situations for knowledge application. Experts will self-consciously exploit analogies, reasoning by related cases, and use other heuristics in order to make connections between previous knowledge and the present case (84). The domain expert is distinguished from the novice not only by having more knowledge for automatic application to situations (though processes of recognition), but by having more strategies (and better control over their use) for "repairing" prior knowledge, recovering when it fails (165). Research with novice learners (e.g., for multidigit subtraction [25a, 193a], and for algebra equation-solving [84]) suggests that systematic patterns of procedural repair are used when prior knowledge fails. These findings imply that repair processes are basic to learning, and may be exploited by instruction so that learners exert autonomous control over learning repair activities (84). The instructional result would be more flexible understanding, ready to meet the novel situations an uncertain future world presents.

2.2. View of the Nature of "Understanding"

Detailed comparative studies of the processes and outcomes of reasoning about problems by experts and novices in different knowledge domains have led to major reconceptualizations of what it means to "understand" a topic (134a). While this issue is one of the most complex of all topics in the cognitive sciences, there are nonetheless several major points of agreement arising from research on psychological understanding. The importance of this topic for education is momentous, since much present school-based "learning" does not result in understanding (6, 33, 153).

The first major point is that understanding is an active process, guided by prior knowledge and expectations. Whether the domain is reading narratives, solving physics problems, or creating an algebraic model of a situation, people expect regularities. These regularities constitute basic categories of experience, "frames" or "schemas," that are associated in memory with prototypic features (163). Schemas bring order into a world that would otherwise consist of entirely novel experiences. Expert learners have highly elaborated and differentiated knowledge schemas that often lead to "automatic" recognition of a problem type and deployment of the appropriate actions to solve the problem (2, 3, 84). Those with high levels of domain understanding also can reason analogically from prior cases, evaluating the utility of discoveries made through such analogies, and reason counterfactually, in order to determine "what-if-not?" (e.g., in mathematics [168], social science [193a], electronic troubleshooting [24a], and medical diagnosis [46]).

A second and related point is that domain experts have well-developed "mental models" of how complex systems function, such as electrical circuits, steam plants, economic systems, computer programs, ecosystems, or aircraft navigation systems. These mental representations are functionally important because they can be used to "run" mental simulations of such a system in order to qualitatively reason about its hypothetical future states and determine "what if?" (14, 69). The utility of such virtual machines in memory is apparent in reasoning about malfunctioning systems, or about the predicted consequences of changes in the properties of a particular system component upon system behaviors. Technical training in military and industrial settings has benefited from these scientific insights (85a, 91a, 185).

A third key aspect of understanding is the rich interconnectivity of knowledge schemas. Research indicates that the knowledge of a novice may be represented in isolated "packets" in memory (62a, 165), so that contradictions may arise between beliefs which have never been brought together before in explaining events. Consistent and coherent belief systems are not easily achieved, but require special educational attention. This is a particularly deep problem in science education (33, 38a, 58, 89). Teachers may need to go to elaborate ends to elicit students' conceptions so that such cognitive conflicts are made manifest, in the hopes of subsequent instructional progress if they can guide students to integrate such formerly-isolated belief "packets". On the positive side of this problem, great power resides in the multiple representations of knowledge in a connected memory system. For then much more flexibility is enabled in paths of thinking about a problem. One perspective or representation may serve much better than another in coming to a problem solution. Knowledge "participates" in various knowledge structures, so that a deadend in reasoning about a problem in one way may be overcome by trying another path of inquiry. Such relational matrices among concepts and skills seem to be "compiled" in memory through experience in working with variegated examples (75a).

A fourth important aspect of understanding is the use of both domain-specific and general strategies in problem-posing and problem-solving (76, 84, 183). Part of the facility of the domain expert resides in the use of powerful strategies for reasoning that are finely-tuned to the characteristics of problems that arise in that space (e.g., strategies for solving algebraic problems, or reasoning in social science).

Finally, great importance has been attributed to the use of "metacognition" for learning (23, 51, 168, 182). This term refers either to *reflective cognition*, one's awareness of particular characteristics of one's mental states or processes (e.g., that list is too long for me to remember; I will make mistakes in multiplying such large numbers in my head), or to *regulative cognition*, one's use of executive or monitoring strategies for guiding mental activities in problem-solving (e.g., time allocation in studying; strategy selection for overcoming lack of understanding in reading). Among the major pedagogical goals arising from this research to date is the fostering of autonomous learners through direct instruction in learning-to-learn strategies, and comprehension-monitoring strategies in reading (44, 170).

2.3. View of Materials Needed for Learning

Massive curriculum reforms in precollege mathematics and science were funded by the federal government in the 1960's and early 1970's, including those of the Physical Science Study Committee, the Biological Science Study Committee, Chemical Bond Approach, Project Physics, and the School Mathematics Study Group (121). Although these projects were designed to produce materials so that students could acquire subject "understanding" of the kind we have been discussing, these materials made their major breakthroughs by providing deep, structural analyses of the subject matter, which were then reflected in the curricular structures that were developed (116, 121). For the past several decades, education has been correspondingly *curriculum-centered.*

The major change wrought through recent learning research in the education sciences is a *learner-centered* view, or what we will call the **"cognitive shift."** Even though educational topics, examples, and subject matter structure and sequence still need analysis and careful design, there is a broad consensus that they must begin with the knowledge states of the learner, and build from there. We know practice with variegated problems is important, but much more basic research is needed to match problems with student knowledge and needs.

Substantial evidence indicates that most present curricula as used poorly promote subject matter understanding (e.g., 57, 58, 68, 88, 92,116, 123, 131, 149, 154). We also know that the lack of specified relationships between traditionally-distinct curricula leads for most students to isolated knowledge structures that correspond but too well to the curriculum boundaries (18, 20, 147). Concerns emerge in the common lack of transfer of school learning to experiential situations outside school in society and work, and in the nonutilization of experiential knowledge (such as invented algorithms for addition and subtraction) in school settings (37, 50, 61, 102, 108, 153, 155, 156, 169). The calls for reform are founded, for example, on cognitive research indicating the conceptual isolation of knowledge acquired in mathematics, science, and language arts, whereas concepts and skills involved in these disciplines are needed in an integrated manner for reasoning and communicating in order to solve real-world problems. Calls for reform also highlight the "inert" nature of much knowledge acquired through formal education, whose conditions of application are left unspecified. And even the most well-structured curricula from a subject-matter perspective may not be learned because of conflicting preconceptions learners have that are derived from experiential knowledge, or because of the limited nature of knowledge representations that are offered (e.g., text only, when pictures or diagrams would help).

Present learning materials have several other major problems besides lack of integration. They are often comprised primarily of referentially-isolated activities, without regard to their meaningfulness in relation to real tasks (153, 164). Prominent examples include syntactic drills in arithmetic and algebra, memorization of vocabulary definitions, rote enactment of cookbook lab experiments, and part-of-speech sentence diagramming. Perhaps not surprisingly, many studies of classroom instruction have shown how little actual instruction takes place of the whole activities of reading, writing, mathematical modelling of situations, or scientific inquiry (10, 12, 168, 173, 179). Documentation of such experiential deficits cries for curricular reform.

In new "functional learning environments," what have typically been characterized as "basic skills" are not taught as ends in themselves, but as component tasks whose fluency is required for success in real activities (26, 50, 53, 143, 168, 185a). Real applications of knowledge to be acquired are at the core of instruction, and students are "scaffolded" as they become increasingly more proficient in taking on parts of the whole, meaningful task, with instructional support "fading" as competencies are achieved (52, 148ab, 153, 154a). The aim of autonomous or collaborative real task performance is explicit from the start, not promised at the end of isolated drill activities with unspecified conditions of applicability. Instructional studies utilizing such methods for reading comprehension (143), composition instruction (12), and mathematical problem solving (168) have been highly successful in improving student capabilities with this approach.

Even such functional learning environments carry with them the newly-documented need for teachers to understand, at an individual student level, the *preconceptions* a student has about the subject of instruction. Substantial cognitive research in science learning shows how proto-theories students hold about light, gravity, motion, heat and temperature, weight and density, biological organisms, and other physical phenomena are unlikely to be integrated with the knowledge conveyed by formal instruction (32, 33, 38a, 39, 40, 58, 60, 61, 74, 106, 116, 122, 123, 142, 193, 194, 201). Science education research suggests that using sensitively-designed curricula where recurrent preconceptions are explicitly recognized, diagnosing and discussing preconceptions and the strengths of formal alternatives, may help students build upon their preconceptions (116). Similar findings appear for the social sciences (193a), writing (12, 26, 58a, 148), reading (6, 96), and technology (148a), although less work with this orientation has been carried out for such subjects. Work with expert teachers has shown part of their success arising from recognizing *types* of preconceptions and developing specific strategies to deal with them (12a, 109a).

A related point, also concerned about individualization, emerges from research on individual differences in experience with and capacity to learn from different modalities, such as text, pictures and diagrams, graphs, equations (38, 89a, 176a, 176b). A principle distinction between text-based and graphically-based modes of learning finds some research support (68a, 119a, 144b), and has critical implications for basic research and development activities in creating and testing new applications of computer technologies that offer unique opportunities for enhancing the visual learning environments of education.

Beyond considerations of individual differences, a core insight of cognitive science has been the utility of *multiple representations of knowledge* for supporting learning, reasoning, and problem-solving activities. Each representational system--natural language, symbolic equations, logical formalisms, pictures, functional diagrams (e.g., of circuits, or processes), graphs, etc.--has specific strengths and weaknesses in the features it provides to support or guide problem-posing and problem-solution processes (13a, 97, 107a). Expert reasoners in a subject area tend to be highly flexible in the representations they choose to exploit for posing and solving problems (84), so a desirable goal of curricular design should be to facilitate fluency in the various representations of knowledge that a student will need to use.

A last and deeply significant way in which curricula must change is tied directly to information technologies. What one "needs to learn" has for millennia been *conditional* on the technologies available for thinking and reasoning. In an oral culture, rhetoric held sway. The ingredients of literacy were dramatically changed with the advent of a written language medium, and later a print-based one (141, 150a). The widespread availability of word processors and other writing tools such as outliners and an on-line thesaurus and spelling checker, as a recent OECD report (26, cf. 70, 148) indicates, are radically redefining what students are doing in language arts. Requisite mathematical knowledge and skills have been similarly contingent on technologies (68, 97, 131, 190). Graphing programs allow students to develop intuitive understanding of relations between graph shapes and equation specifications that formerly required laborious hand-plotting of point. Symbolic manipulation programs available for $100 can "get A's" in college mathematics courses, and suggest redefinitions in what one needs to do and learn from precollege mathematics courses. Databases in science and history are being used in secondary schools throughout the country to foster original inquiry by students, previously possible only with great labor. The professional subject-matter teaching organizations such as CBMS (55), NCTE (160), NCTM (131), NSTA, and more broadly, NSF (131a) have been hard at work redefining curricular priorities and topics. The reasons are that one may now treat topics with information technologies that were not possible at all before at the precollege level (e.g., systems dynamics modelling; robotics; graphics animation), and that some topics should now be omitted from curricula (e.g., long division) because low-level algorithmic activities formerly taught may now be automatically carried out by the computer (68, 131). Many of these computer uses have been designed to overcome cognitive or instructional "bottlenecks," and thus emancipate the learner.

2.4. View of What Pedagogical Tasks and Strategies are Effective and Why

With new conceptualizations of the learner, and of appropriate curricula, comes a new understanding of what the pedagogical activities of a classroom should be in order to promote effective learning and understanding. Many of these insights are implicit in what has already been said, and many of the techniques have been used by expert teachers for many years. But there is a new specificity to why such techniques work that supercedes previous understanding. Clearly much more attention to the preconceptions of individual learners is needed for formal knowledge to be acquired by more students through teaching and learning activities. This requires "knowledge diagnosis" of a kind that is more labor-intensive and teaching-relevant than traditional classroom assessment measures (71, 116). "Linking" activities have teachers solicit from students, as well as provide, connections between what is being learned and previous learning. Linking is seen to aid knowledge transfer processes, even among traditionally poor learners (23, 67, 142, 143).

A central lesson from education science investigations of classroom learning is *sociological* Individuals create, revise, and contribute not only to their own knowledge but that of the culture. But education tacitly espouses counterproductive belief systems for what knowledge is, and what a learner's role is in the knowledge acquisition process (50, 124, 133, 168). To facilitate this awareness of the purposive and constructed nature of knowing--rare among students but common in the disciplines--the teacher needs to create a *community*, in which thinking and problem-solving of the kinds required for the discipline(s) under study is contributed by all members of the group (12, 22, 52, 89, 147, 153). Several kinds of activities appear necessary for this community to be established: (1) the teacher thinks-aloud about problems, including ones that are novel to her and for which answers are not immediately apparent, describing reasons for making certain strategic decisions and not others, working through reasoning steps; (2) the teacher solicits contributions to this process from classroom members so that they come to collaborate in the problem-solving process, even when they would be unable to carry out the whole task alone; (3) students come to take on "roles" or subtasks in complex collaborative problem-solving, and rotate in these roles; and (4) group discussions take place on such processes, reflecting on and consolidating what has been learned. Small group learning, peer tutoring, and apprenticeship learning have also been demonstrated as effective techniques with implications for educational technology development and use (50, 52, 78).

The role of reflection in these processes deserves special mention. Expert problem-solvers routinely pause on completing the solution of difficult problems and reflect on what has been learned--whether there were reasoning dead-ends, inept analogies, or productive generalizations that could be useful to remember for the future (168). New information technologies make possible the recording and abstracted playback of problem-solving sessions for such reflective analyses (51).

2.5. View of the Role of the Social Context in Learning with Technologies

There is also a broader recognition than in the past of the potent roles of social context in the learning process. Research on teacher cognition and classroom activity planning, peer collaborative problem-solving, homework and parents, and on motivational and attributional aspects of learning activities has contributed to this new understanding (50, 102, 120).

Curricula and tools for learning in the classroom rarely have direct effects on learners. The lessons and empowerments that they offer are typically mediated through the activities, expectations, and shaping influences of the teacher, the students' peers, and parents. Correlatively, the learning a specific individual is capable of is not solely a characteristic of that person, but of the social contexts in which such performances are carried out. The shaping characteristics of learning environments are thus complex and multifaceted, and we have only recently begun to chart the dimensions of their influence (50).

For example, teachers can make a difference in whether they create and maintain an open environment in which making mistakes is an accepted part of the learning process, and in which different approaches to problems are welcomed as opportunities for group learning. Such an environment appears to have shaping influences in whether a student treats work on a problem as an opportunity for learning or as an occasion for failure and diminished self-worth. A student's concept of self-as-learner thus has important causal influences on both achievement motivation and reactions to learning feedback (63a). And negative teacher expectations for a student's performance often become self-fulfilling.

Social relations with peers in the classroom can also be harnessed to contribute to cognitive growth. Numerous studies in a Piagetian tradition indicate that peer discussions of strategies for solving a problem may serve as important facilitators of cognitive growth, by making explicit different beliefs and arguments for their warrants (148aa).

3. What Specific Research and Technology Directions Could Bridge the Gaps?

Given these new understandings in the education sciences, how should educational practices be influenced? How might specific research and technology directions in education bridge the gaps we have described? What *changes* would need to occur? Cognitive, social, and instructional science studies have documented an incredible number of specific learning problems that arise in education. Examples of "basic competencies" often served up to illustrate what is lacking or deficient are insufficient vocabulary, grammar, procedural skill in algebra, or calculational talents. These are but symptoms of deeper problems. Training or longer school days aiming for better performance on the achievement tests crafted for these diagnostic purposes misses the point. Education must help students learn to put their minds intentionally to work in categorizing, analogizing, critiquing, designing, inventing, modelling, and like activities. How can we better help students learn to comprehend and imagine as they read, to compose text for expression as well as for learning, to think mathematically, to reason scientifically, to reason critically, to take control of their own education within and beyond formal settings? The grassroots and research community calls for focus on "complex" or "higher order" thinking skills express these aims (44, 170).

We have seen how the cognitive, social, and instructional sciences have transformed views of the learner, of understanding, of curriculum, of pedagogy, of social context. How might these works find application and continual renewal through research and development activities with computers and related computational media? As an organizational strategy, we have grouped the emergent trends and themes from our consultations with experts in the field into five categories of goals. These goal categories, overlapping to some extent because of the *system*-based nature of what makes learning work (120), correspond to those of our analysis of what has been learned. These goals present a framework within which we can place the various research and development directions and themes considered central to plans for improving the quality of education.

For each category of research and development activities described as goals, we provide a brief rationale linking it back to the research, and remarks concerning issues of overall priorities. It is important to observe that many uses of technology now common in educational practice (11, 186) were *not* considered high priority for federal support by our respondents. These paradigms include standard drill and practice software (especially in arithmetic and language), some rigid branching CAI programs, and in general, "computer-based management" approaches to computer use to mechanize existing testing procedures, scoring, and reporting.

We also note that a tension exists within the field of education science as applied to educational technology and evaluation issues. The tension is between making technologies that can be evaluated as "working," given present achievement-test metrics of effectiveness (not measuring understanding), and making technologies that enable students to engage in qualitatively different and superior learning experiences, better geared to providing "learning as understanding," but for which new measurement techniques need to be developed (116, 120). New work in cognitive psychometrics at the Educational Testing Service and other laboratories is moving in this latter direction (28, 77, 117b). Strategies for providing measures of accountability in the educational technology field are in flux because of this basic issue. For example, the classic benchmark is Benjamin Bloom's findings of a "2-sigma" advantage for individual human tutoring over conventional classroom-based instruction (12b). This means that the tutoring method puts the *average* student who is tutored in the *top five percent* of a student population conventionally taught. This dramatic result can serve as a goal for any of the technology-enhanced methods of education, once measures of conceptual change are determined for the cognitive-shift paradigms we will be outlining.

In addition, while it is highly unlikely that technology is appropriate for every activity in education, our analyses are technology-focused since that is our charge in this report. Given this constraint, we need to be sure to focus where indications are that research and development work in this field will have significant payoffs for investments of effort, talent, and costs. We also highlight opportunities for educational benefits arising from technical developments that many believe can be fruitfully exploited by the research and educator communities.

It is necessary to distinguish education from training. Many technologies, from the business tools of office automation to the interactive videodiscs for subject-matter learning in military training have quite a restricted focus. They are designed for very special environments, with deeply-engrained assumptions about the social environment, the age and goals of its users, and with narrowly-defined performance objectives. While we hope to learn from such technologies and to exploit such inventions whenever possible, they are not easily or even desirably adaptable for classroom uses for education. It is certainly important to recognize that research and development in business, industry, and military training does not translate into educational technologies for precollege education (28).

Before characterizing high-priority categories of R&D activities in educational technologies, it is important to briefly sketch the dimensions of technological development trends, and to set out where educational technologies are now in schools. While unpredictable factors may alter these considerations (e.g., the pace with which emerging superconducting materials will find their way into everyday powerful computers), they serve as influential constraints to heed in the directions of R&D the Federal government decides to pursue.

3.1. Advancing the Educational Technology Available to Schools

There are important constraints to recognize in the pace of change with which new technologies for education are coming into schools, and in how new programs are created and marketed. Recognition of these constraints is important, for they have not figured in much R&D planning for educational technologies. Given projected continuation of the organizational behaviors to be described, the federal government can either work to confront and overcome the constraints with novel programs of support and incentives, work within them, or implement some mixed strategy. In any regard, closer attention to present organizational constraints in the design and implementation of research and technology development in education promises to improve the impact of R&D on educational practices.

Constraint 1: *The installed base of technology defines present markets in educational computing.* During the past decade, schools and parent-teacher organizations moved quickly and often at a grassroots level to buy computers for classroom use (11). While this has been important in familiarizing teachers and students with fundamental operating concepts of computing, and basic paradigms for software use, it is becoming apparent that there are side-effects of these early moves to computerize the classroom. Schools buy new machines to match their old so as to capitalize on teacher training, student familiarity with programs, and the installed base of hardware and software (186). As many analyses of computing in organizations have shown, there are large "buried costs" of new technologies (5, 101). In this case, they include the costs of teacher education, student familiarization, time for practitioners to develop skill in making a specific technology work in the classroom, seeking out and evaluating alternative options for updating technologies, hardware and software technology maintenance and upgrading, renovation costs to retrofit existing spaces for the electrical, space, and furniture needs of computer technologies, etc. The schools' attention to such costs revealed with the installed base strategy is parallel to concerns in business when they consider upgrading technology, as IBM found with their 360 series of computers.

With respect to hardware, the Apple II family computers are the dominant precollege machines (with over 1 million in schools, mostly Apple-IIes, amidst computers from IBM, Commodore, Tandy, etc.). Schools also rarely get rid of equipment, but instead find a lower "niche" for its use, so that older computers such as Texas Instrument-99s, Commodore-PET computers are used for barebones programming instruction in the early grades. 128K (kilobyte) machines are not yet the majority of microcomputers in school use. Since the dominant Apple-II family computers are rugged machines, professional educational software developers and publishers we interviewed consider it likely that they will remain in school use over at least the next 5 years. Apple IIgs computers, which have more powerful graphics, audio, and processor capabilities, are coming into use slowly, and are the most advanced computers such developers have begun to create software for commercially. Market surveys indicate that schools are acquiring this level of machine primarily because the Apple IIgs run their installed software base (largely for Apple-II family computers). By 1992, IIgs's are expected to be standard 4 megabyte (4000K) machines, and widely available in schools.

An emphasis on the higher-end hardware recommended in previous policy reports misses the point of what schools can or want to do in their purchasing within at least the next 5-10 years, given current trends in financing educational computing. This point applies to IBM-PC/ATs or Apple Macintosh computers, much less university-level advanced function workstations such as Suns, Microvaxes, Macintosh-IIs, or IBM-Personal System computers. Yet it is true that systems of this level are needed to run graphics-intensive and multitasking software applications typical of integrated tool environments (129). They unfortunately do not allow schools to use their installed base. For example, none of the Apple Macintosh computers can run Apple-II family software. The more successful educational software developers also will not take the financial risk of working with "niche" machines (in particular, those with only a school but not a home market, as in the case of the now defunct IBM-PC Jr.).

Finally, a key figure to note is the 10-15 year time period from when a new chip is developed in sampling quantities in laboratories to when there is likely to be an installed educational software base in schools that uses the chip. From lab chips to shipped computers using those chips has typically taken 3 years, developing an operating system for the chip takes 3-4 years (e.g., IBM OS-2) and may take longer as chips increase in complexity, 1-2 years more for software developers to use the operating system to create applications, and several more years at minimum for the installed base of the new level of computer to reach the critical mass required to attract a broad range of developers to create applications specifically for schools.

Constraint 2: *Since little educational software is purchased by schools, educational software development is financially risky for commercial developers. Needed research to make programs effective cannot be afforded.* Software purchasing behavior of schools is also very conservative. In Fortune 1000 companies, the budget for software typically exceeds the hardware budget, whereas schools only spend 17% of their hardware budgets on software. The success of software sales in education, even for tools such as word processors, is often explicitly linked to textbooks, and expected gains in achievement test scores. And schools on average purchase only 14 software programs per year of the thousands produced (186). Parents spent six times more last year (over $200 million) on educational software than did schools (Future Computing).

Over 11,000 educational software titles have been produced, and 150 new ones appear each month, with a bare minimum of testing, primarily to overcome functional flaws in program operation. Very rarely do companies have the money available to engage in formative testing in classroom situations to see if the product can be used effectively by teachers, or whether students learn from it. Evaluations of educational software consider only 5% of present products outstanding, and even these evaluations are not based on observations of classroom use but professional evaluator assessments based on first-hand inspection of the program. The evaluation principles used fall seriously short of the cognitive evaluations we have described as central to closing the gaps between learning theory and educational practices.

3.2. Emerging Computing Standards for Undergraduate Educational Technology

It is critical to heed the hardware and software technology that is in our schools today, and to compare it with what is being used as the development and testing environments for new educational technologies in research universities, centers, and laboratories. Perhaps the most instructive comparison will be with undergraduate education.

The minimum hardware requirements defined at the undergraduate educational computing level are known as the "3M" machine--a million-instruction-a-second processor, a bit-map screen display with a million dots (pixels), a million bytes (megabyte) of main memory, virtual memory, and a LAN connection (9, 129, 202). For example, such specifications provide the capacities to display and transform interactively images used for learning in mathematics (e.g. graphs), science (e.g., interactive simulations), and with text (e.g., relational databases, idea organizer programs, hypertext). Berkeley UNIX is the operating system being used in these machines to allow for multi-tasking and some software transportability, and windowing systems likes CMU's Andrew or X-Windows are being used so that the programmer-side of UNIX is not visible to the student user. This approach has been called "interpersonal computing," since it links together a student's advanced function workstation and a mainframe fileserver so that it appears to the student as if one has all one's data and programs locally (electronic mail, remote access to large databases, statistics). Such workstations with educational discounts meeting these specifications from Apple, DEC, IBM, and SUN Microsystems are now available in the $5000-$8000 range and are expected to reach the desired $3000-4000 level within two years (10% of a student's four-year tuition).

3.3. Theory-based Educational Technology Research and Development Strategy

It is important to recognize that the relationship between theory, research, and technology development in education is (to some measure) different than many other fields, which have sharp distinctions between basic and applied research. Many leaders in the field now recognize that the theory-practice link for educational technologies is not a one-way application of knowledge to action (e.g, 65a, 82). For when a theory of learning and pedagogy is embodied in an educational tool, and then tested in real contexts of use, feedback is provided on the soundness of the theories, not only the tool. And the very nature of the settings in which the technology will be used and in which the learning will occur should be used to shape the design and features of the technology. The theory itself will develop responsively through such applications to learning in real settings. Many hope that technologies can better enable a "cybernetic education system," in which feedback loops between outcomes and practices can provide a more adaptive, dynamic educational system of learning and teaching activities than previously possible (28). This aim will require new kinds of assessment measures that characterize conceptual change and cognitive growth through levels of proficiency for valued education outcomes.

These observations recommend a mode of work that incorporates the insights and activities of teacher/practitioners, education science researchers, technology developers, subject matter specialists, and, to insure real-world market penetration of research-based materials, professional publishers (25, 112, 113, 120, 121). Our policy discussions in the final section of this report elaborate on technical and cost requirements of work models incorporating these groups and their activities. Related discussions of interdisciplinary integration of the kind required to advance the practical impacts of this field are available (45, 87).

3.4. Changing What Students Do

Research on the nature of the learner in the cognitive, social, and instructional sciences (earlier described) has profound implications for what students should do in order to learn, whether in schools or other settings for learning such as community centers, clubs, or libraries. We also must emphasize the importance of universal access to quality uses of educational technologies. Research has indicated that in addition to the knowledge and technology gaps we have highlighted between schools and society, there is a highly divisive gap that puts at a disadvantage students in rural schools, the largely minority students in poor urban schools, and female students (11, 43, 50, 65, 120, 178). Federal attention is needed to insure that the changes outlined here for what the research says students should be doing in education involve these groups and settings, so that these education environments may take the fullest advantage of the fruits of educational technology research and development.

There are a variety of paradigms that have become established in the research and development communities during the past decade for building and using educational technologies. What we describe in the sections that follow are the key areas that were highlighted by experts in the field as important priorities for Federal support.

An important observation is that ***very few of the priorities experts recommended are now in use in schools.*** Although survey data indicate that tools such as word processors and micro-based science laboratories are entering the classroom, most present uses are for drill and practice and tutorial CAI (11, 64, 65), which previous survey reports have concluded offer little to improving student understanding (25, 112, 113, 120). Unfortunately, in only a few cases are paradigms recommended by our experts being used to *commercially* implement educational technologies that schools could hope to exploit within the next five years. For these reasons, federal efforts should closely examine the ways in which research and development activities could be more intimately related to technology transfer activities of the kind that software developers and commercial publishers are technically able to implement with appropriate incentives. Further analyses of the nature of possible Federal R&D/commercial relationships are provided in the concluding policy section of our report.

The major categories for our discussion of "changing what students do" will be intelligence extenders, microworlds, "intelligent" tutors and coaches, networking, and hypermedia and multimedia learning environments. It will become apparent as we examine other topics in subsequent sections--changing how we track learning, changing what's taught, changing what teachers do, changing the schooling environment--that there are intimate relations between these different facets of the student/teacher/ materials/ environment system. But we believe these categories offer helpful distinctions for thinking about the ways in which experts recommended how research and development activities in the cognitive, social, and instructional sciences should change education, and what technologies it should employ to support its work.

Since the cognitive view of education is student-centered, it is no surprise that the bulk of priorities we will discuss involve changing what students do. It is also important to note that these categories have been reasonably distinct in modern research and development efforts. Although there have sometimes been ideological grounds for these separations, we believe they are primarily due to hardware and software limitations and the early stage of work in the field, whose scientists have tended to direct their efforts to one or another paradigm. There are many reasons to believe that integrating these paradigms of information technology use in education to create hybrid systems will be important to do. For example, knowledge representation methods for inferring a students' conceptual model of a domain now used in "intelligent" tutoring systems and coaches could complement the microworld approach, or a student's strategies for using tools in some learning activity could be inferred and result in hints from an "intelligent" help system. We see comparable trends in the "functional eclecticisms" of today's interior design directions, and in combinations of rule-based, object-oriented, and logic-based paradigms for new high-level programming languages (13).

3.4.1. Intelligence Extenders

There is a major class of tools for learning and problem-solving, also found to be very useful in teaching, which have been described as "cognitive technologies," "intelligence extenders," "cognitive workbenches," or "mental prostheses." These tools make qualitatively easier the specific mental activities involved in complex tasks such as collecting information and crafting idea structures in writing, comprehending intricate mathematical relationships through dynamic graphs, and designing and running experiments. What they have in common is making more accessible, with less mental effort, the achievement of what are considered to be "complex" acts of mind. Development efforts of this type often create qualitatively different learning and teaching experiences. Many of our experts suggested that for education "machines that think" may be less essential than new tool systems that enable students to better express and build on their own intelligence and creativity (53, 65a, 70, 98, 132, 154a, 166).

What computational media commonly afford in such applications is great speed and accuracy in the transformations of symbols, including pictures, text, diagrams, numbers and sound, that allow for extensions of human intelligence. Many different tools may be integrated in such cognitive workbenches, facilitating multitasking and the construction of single documents comprised of multiple media. The rapid interactivity of these tools enables the thinker to engage in the incremental refinement and revision processes--whether the task is algebraic modelling, persuasive writing, or planning a scientific experiment--that have been associated with expert performance in a host of disciplines (84). These rapid interactive properties, developed at Xerox PARC for business and programming environments (13, 176), are now standard features of the Apple Macintosh environment, and in "windowing" packages for IBM and other computers. As we have seen, they are also central to university-level educational computing, as a key component of the standard arising from planned synthesis activities of the InterUniversity Consortium for Educational Computing (based at Carnegie-Mellon University).

Such tools are important for they help close the gap between the worlds of school and the workplace. Content delivery is comparatively inefficient from the perspective of nearly all the educational technology developers we spoke with, since a new program is needed for every new piece of curriculum. It is also inefficient for schools, because teachers and students must often re-learn how to use the different software programs because of inconsistent design and functioning. And as designed today, there is too much emphasis on the technology's surface features, which are created to appeal to and hold student attention through extrinsic motivation. Various experts considered that tools will probably have the most payoff, especially those used in reading and writing. For under $100, a word-processing program designed for student 8 years-old and up can be purchased--with 60,000 word spelling corrector, and combined thesaurus and 50,000 word dictionary.

Micro-based laboratories available today provide compelling examples of how we can help students learn science by doing it. The Lego-Logo Project at MIT, in which elementary students write Logo programs to control Lego machines, reveals how one can connect programming and real-world objects such as gears, levers, and sensors, so as to introduce key concepts in physics, engineering, and robotics through an experiential approach (132).

Developments are now approaching second-generation, or "integrated" tool levels. Present systems being commercially developed, unfortunately with minimal research support, are for early reading and writing, K-6 mathematics, and micro-based lab science. They will be customizable by teachers and publishers for different curriculum areas and topics. The analog in the business world is dBase III, which is a powerfully general database system complete with a programming language for creating database applications. While it is acknowledged that there are better database programs available, this one has spawned several hundred companies that all make applications (e.g., accounting or inventory overlays to dBase III). The same has happened with Lotus 1-2-3 in the world of spreadsheets and financial modelling. Various experts consider the development of comparably powerful "engines" for education to be a high priority, expecting that similar branch-off developments would occur, leveraging the impact of Federal investments (112, 118). Creating tool "engines" is just the approach taken in the past five years at the university level, lead by Project Andrew at Carnegie-Mellon (129), Project Athena at MIT (9), and Brown University's IRIS Project (202).

This approach thus builds on substantial prior investments in software and hardware engineering by industry, business, and university education, and would represent an important continuity between the precollege and college computing experiences.

Present precollege efforts underway with federal foundation support along these lines include a tool environment for scientific inquiry (Inquire: Bank Street College: 89), graphical tools for science and mathematics (e.g., Sketch: Carnegie-Mellon; Functions, U. California, Berkeley), for systems modelling and theory building (TERC/Lesley College: 190), for network-supported collaborative research in earth science (Earth Lab: Bank Street College: 133a) and environmental science (TERC/National Geographic: 189), a set of tools for learning and doing statistics (Bolt, Beranek & Newman: 158), a decision-analysis support tool environment for social studies (IDEA, New York University: 147a), and a powerful environment for students and teachers to create such tools, called Boxer (U. California, Berkeley: 62, 63). For example, the Modeling Project (TERC/Lesley: 190) allows high-school students to learn about systems dynamics and system modelling by using icons to build models. In building models of population growth or toxic waste impact, icons would represent levels (e.g., population; pollution) and rates (births/deaths; accumulation/absorption), and interaction is used as the calculation mode to "run" the model. Thus students can work intuitively with the basic ideas of differentiation and integration which formerly required formal instruction in calculus.

What these and other efforts begin to make apparent is that learning general purpose programming languages is an anachronism unless one plans to become a computer scientist or programmer. While programmable functions will be available for many of the tools above, the clear trend is toward creating application-specific, special-purpose programming languages for tool use and control, and these are often not even being called "programming" any longer because of the technical image that conveys.

Many experts whose advice we sought placed high priority on creating many more tool environments for precollege education, that should be designed to simultaneously provide powerful new learning environments for education, and "mini-research laboratories" for studying the acquisition of complex cognitive skills (82). They suggested that schools should be involved in having students use cognitive workbenches, such as outlining tools and text-editors, database access and information organization systems, drafting and animation programs, theorem-proving assistants, algebra assistants (such as those under development at Bolt Beranek & Newman; Harvard Educational Technology Center; Rand Corporation), spreadsheets, graph plotters, and multimedia design tools. A key educational goal in these efforts is to provide means for students to make conjectures and hypotheses, just as in the worlds of science and society, that can be tested and discussed with a teacher's guidance (50, 135). Numerous experts also stressed the need for enhancing students' capacities to design communications, to be able to manipulate the language with ease and grace, through written and oral expression, and graphical means (26, 70). Communicative expression permeates virtually everything a person does, and cross-cuts the entire curriculum. Research examining effects of using word processors in education has barely scratched the surface of this important, broader problem (26, 148).

The most liberating of the uses of technology in this category which we know about are those invented for exceptional students (127, 154a, 159, 191). Reports have begun to appear of how educational technologies may remarkably enhance opportunities for the physically handicapped (e.g., cerebral palsied, at Francis Orthopedic School, Riverside CA), for blind (e.g., Tennessee School for the Blind), deaf (Clark School for the Deaf/Smith College), learning disabled, and hyperkinetic students so that they can be mainstreamed into regular classes from special educational settings. Some of the innovative projects include braille word processors for the blind, specially- designed materials for teaching English syntactic structure to improve the reading and writing skills of the deaf, and the use of speech synthesis output and graphics-tablet generated speech to initiate and then support communicative expression for students with either no or very limited oral language (e.g., autism, cerebral palsy, Down's syndrome: City of Hope National Medical Center & George Washington University). Many of the projects foster a new independence on the part of such students.

While these are some of the most moving cases of how technology may enable the expression and fulfillment of human potential, more planned synthesis of research and documentation of projects in this area is called for, so that these effects can be widely replicated.

3.4.2. Microworlds: Context-Based Learning

Microworlds (113, 144) are uses of the computer for providing dynamic models of systems, or small parts of systems, that students can explore and study, either without instructor support, or with instructional guidance built into the program ("guided microworlds": 198). Such paradigms for learning have also been described as "discovery worlds" or "simulations" (although many earlier simulations did not allow students to change the properties of the systems, much less construct their own).

Such microworld systems have been created for early physics learning (*Dynaturtle*: MIT: 60, 199; *ThinkerTools*: Bolt Beranek & Newman: 198), for exploring electrical circuit behavior (*Sophie* [24a], *Quest* [196, 197]: Bolt Beranek & Newman), for economic systems (*Smithtown*: University of Pittsburgh: 118), and for physical systems such as a steam plant (*Steamer*: Bolt Beranek & Newman [185] , UCSD [91a]). Simpler versions of simulations developed commercially for microcomputers (with little learning research input) include *Geography Search* (Tom Snyder Productions), *Island Survivors* (Holt, Rinehart & Winston)--part of Bank Street College's Voyage of the Mimi multimedia series for mathematics and science education, and the microworld *Rocky's Boots* (Learning Company), for creating logic gates.

Microworlds are seminal learning tools because they highlight cognitive objectives demonstrated to be central to "understanding"--i.e., how things work. For example, those proficient in scientific reasoning have mental models of the physical system in which phenomena of interest occur, and are thereby better able to predict what will happen given certain changes of system design or system variables (14, 59, 69, 84). Insofar as using microworlds or simulations encourages the formulation in memory of knowledge structures and mental processes that allow such science understanding, they serve key educational goals, often overlooked in a textually-based science education (116, 120). Recent studies of precollege science textbooks show that often more new vocabulary is introduced in science than in a foreign language text, with insufficient attention paid to prior conceptions, visual and interactive experiences of the world, or of world models (116). Research needs to determine effective designs for learning and teaching activities with microworlds, and their place in relation to experience with the added complexities of real world systems. New microworld topics for R&D from experts we interviewed included ecological simulations so students can examine science-technology-society issues such as acid rain, toxic wastes and underground hydraulics, sewage and water supplies, and depletion of natural resources such as rainforests. The Vivarium Project (Apple Computer, MIT: 132) aims to provide future microworlds where students will be able to craft worlds of realistic animal agents, and then "play them," watching how the animals interact in an ecosystem.

The strength of microworlds from the perspective of research on the nature of student learning and understanding is potentially great. Students can learn by doing, by acting on microworlds rather than merely observing phenomena take place in demonstration mode. They may acquire understanding of the properties of systems and relationships among changes in their properties through their actions upon the systems. Some microworld systems let students build or program their own worlds, and they can then explore how they work, examining the consequences of changes in their properties. An example is the microeconomic simulation Smithtown (118), in which students can vary price and population and observe effects on demand, and use tools such as electronic spreadsheets and graphing programs to support laboratory investigations.

Microworlds can be constructed for close resemblance to real-world activities, so that transfer of learning from working with the microworld and the world of concrete action are closely coupled. New actions that are possible with these microworlds--due to the ability to make changes of scale in space, time, size, and relationships--allow for other powerful teaching and learning opportunities (112). Imaginary microworlds can also be constructed-- non-Newtonian universes and the like--which offer new capabilities to bring to life and render apparent for students things that they could never see or imagine without the technologies (109). Generally, multiple learning paths are made possible that have much in common with "hands-on learning" with physical objects advocated in the science curriculum reforms of the 1960's and 1970's, but which introduce the novel opportunities just described (as well as limits--since a model is never complete).

Support is needed for R&D at a much higher level than currently available for creating microworlds for student use in schools and other learning settings. Few laboratories have had projects of sufficient duration or with the right organizational partners to allow for commercial development and widescale implementation of this learning tool paradigm. Stable programs of scientific research to provide basic knowledge of microworld learning for different subject areas, innovative tools for creating microworlds more broadly, and microworlds to be co-developed for key curriculum areas in cooperation with software developers and publishers, are all required for this paradigm to find its appropriate place in education.

3.4.3. "Intelligent" Tutors and Coaches

The "Intelligent" Tutor paradigm, which has been developed over the past 10-15 years in research laboratories, relies heavily on artificial intelligence and cognitive theory, methods, and programming languages. Some of the most elaborated scientific theories of learning and memory have been incorporated in their development (4, 109, 175, 192a). The term "intelligent" is used because such tutors can by themselves, once programmed, generatively solve new problems of the type they are designed to teach, even though answers for those problems have not been programmed. This paradigm has students work on problem-solving tasks, and then from their responses, builds a model of the student's level of understanding in terms of specific rules and knowledge representations. A theory of instruction for the tutor's knowledge domain is also part of the program. It is then used by the program to offer individualized instruction, reactive to the specific understandings a student is inferred to have. Some experts we consulted find this paradigm appealing, since it "automates" the delivery of instruction and may come to approximate the dramatic improvement in level of student learning found in human tutoring research (although obviously not providing social-affective support, help with unpredictable problems students may have, etc.). They argue that the problem of growing teacher unavailability, particularly in the areas of mathematics, science, and technology education, can be in part met through such technologies. Several existence proofs are offered in the Lisp Tutor (Carnegie-Mellon: 4a), in which undergraduates take a semester-long course in introductory LISP programming with the Lisp Tutor, and the Geometry Tutor (Carnegie-Mellon: 4), at the classroom-testing stage, which teaches geometry proof skills in junior high school.

Intelligent Coaches offer more free rein to the student, but at the expense of requiring considerable sophistication in a pedagogical theory of coaching and hints (30, 175). We presently have little scientific understanding of how to build coaching systems such as West (developed for informal learning of basic arithmetic in a game environment at Xerox PARC: 30) that promote effective learning (25). Coaches allow the student a great deal of control over the situation, and do not inflexibly correct errors in student responses that deviate from optimal performance as in Neo-CAI. The communication problems inherent in coaching systems seem to be solvable only under very special circumstances, such as in the especially constrained task domain of WEST. Solving this communication problem, given the intricacies of natural language understanding, would entail putting almost as much structure on the curriculum as older CAI programs (e.g., PLATO, TICCIT).

The key problem in the near-term with the intelligent tutor and coach paradigms is that they are very capital-intensive and require very advanced computing power, technical knowledge, and art (25). Only a few laboratories in the country are presently equipped with the advanced programming environments and hardware, and the research and development talent in computer science, cognitive psychology, artificial intelligence, and psychometrics that is required for quality work with this orientation. This basic science community in artificial intelligence and cognitive theory is hard at work on the problems of knowledge representation, expertise modelling, and student model-building. Less work has focused on providing an empirical basis for the theory of instruction/coaching built into such systems, or at the "microsystems" design level, in which the classroom conditions for their effective implementation is examined (50, 120). Such research, investigating the knowledge, strategies, and practices of expert teachers and coaches in real educational settings, is considered a high priority for informing these efforts (117a). Several experts suggested that this approach would benefit from having new designs in which students help resolve the ambiguities of the student model being dynamically created during instruction. Presently, it is a difficult technical problem to infer the student's knowledge states from responses to problem-solving tasks, as efforts in understanding the development of subtraction skills (Xerox PARC: DEBUGGY, 29, 192a) and simple Pascal programming indicate (Yale: PROUST, 95b). Students could select one of a set of states of knowledge the program presently has insufficient data for distinguishing, in effect making the knowledge diagnosis task a collaborative one between student and computer.

In the sciences, Quest (Bolt Beranek and Newman: 196, 197) has been used as an intelligent tutor to teach electronic circuit troubleshooting to high-school students, and Guidon (Stanford: 47) is used to teach medical diagnosis. There are also numerous specialized tutors for very small learning tasks that have been developed for commercial or military training, with little application to precollege education unless it is vocational. Other experimental ITSs are now only partially implemented, but begin to show the magnitude of cost and scale for a broadly-used approach of this type: Proust (Yale: 164a, 117b, 177b) and Debuggy (Xerox PARC, CMU: 29, 192a). Our experts consider that because of their costs, it is now most likely that intelligent tutors and coaches will enter educational practice eventually through programs of work initiated by business and/or military research and development. But since these systems are unlikely to match the needs of precollege education, funding needs of new efforts directly working on problems at this level should be better capitalized than at present. The intelligent tutor approach seems likely to be most effective in mathematics and some topics in the sciences. It was generally noted by experts we consulted that even with the technical complexities of knowledge diagnosis and student modelling this paradigm requires, such uses of technology in education will be possible on a broad scale by the end of the century. Advances in the basic science required for success along these lines are considered important to inform next-generation learning technologies and theories (25, 112, 113,120).

Present estimations of development time and costs of such circumscribed intelligent tutors range between 500-1000 hours development time per hour of successful lesson, with minimal use of graphics and no video. For more open-ended tutors, where natural-language like dialogs are offered, we can expect much higher development costs. For comparison, we note that a single university course (non-computer, but using video extensively) at the highly-regarded Open University in England takes a team two years and over

$1 million to develop. One expert expects that it would cost $1-2 million to create each tutor of this type for procedural skills in select areas in mathematics, English grammar, phonological decoding, and some aspects of chemistry and biology. These methods are unlikely to work wherever understanding and declarative knowledge, and not only procedural skill, are required for success, as in word problems, reading comprehension, and those areas of learning requiring huge fact bases (e.g., spelling, science). These areas where such tutors do not work are thus high priority research areas. Such work would be advanced by much more basic research on expert teachers' knowledge used to teach such non-procedural areas. More research is also needed on conditions under which such systems are useful in learning, or serve as a crutch, providing answers as hints if students are having special difficulties.

It is important to distinguish the diverse scientific groups working on variants of the student-centered cognitive approach to education science and technology development, and further developments of computer-assisted instruction in the 1960's traditions. Advanced systems for instruction in calculus (Stanford) or set theory and logic (New York University), build on technical/theoretical developments in neo-behaviorist learning theory during the 20 years of development of over 10,000 curriculum hours of computer-based instructional materials behind the approach of PLATO and TICCIT. A major difference is that these systems are not concerned with changes in the nature of knowledge representations of students taking place with learning, but mathematical models of performance variation with practice. Among the experts we consulted, the cognitive shift in research studies during the past decade in the education sciences poses fundamental problems for this previous perspective. They argued that since it is people who are learning, it should be constraints in their knowledge (such as preconceptions) that should determine how learning and teaching transpire, not the structure of curricular materials. They ask, why should the structure of the problem types of the curricular domain be highlighted to the exclusion of the cognitive and social contexts in which prior understandings arose and in which new education is made possible?

3.4.4. Networking

The advent of communication satellites, local area network technologies for linking together computers, and the use of modems for remote telecommunications has changed the kinds of work that can be done in education, and has potential for positively changing the nature of communication within educational settings (99a, 24, 26, 135, 136) as well as in the scientific community (189, 192). As we now know from the case of the telephone (but never predicted at the time of its invention), changes in communicative structure have dramatic social consequences. How could these be positively exploited for education? Many experts noted how networking in effect "breaks down the walls" of the school classroom, allowing two-way flow of documents, messages, and interactive dialogues that extend the material and intellectual goods that a class has available as learning and teaching resources. More remarks on these "environmental" aspects of networking are provided in subsequent discussions of changing the school environment.

Clearly the kinds of activities students participate in for learning may also change with networking. But how should they? Several prototype projects, Earth Lab (Bank Street College: 133a) and Kids Network (TERC and National Geographic: 189), offer some direction. In each case, students will be involved in doing collaborative science, collecting original data either remotely, throughout the country (on acid rain, as in Kids Network) or in coordinated efforts locally (in New York City for the Earth Lab Project). In these cases, networks allow for the coordination of learning and teaching activities across classrooms throughout the country, or across individual workstations within a classroom. In other efforts originating from UCSD and University of Illinois, cross-cultural communication networks established between the US, Japan, Israel, England, and other nations are being used to coordinate joint science inquiry by students on astronomy and ecological issues, and to compare and contrast cultural differences on these topics (26, 114).

University-level research and development work in this area has focused on defining standards for what is described as "interpersonal computing," in which a student's computer workstation has high-level local computing power but also provides an invisible gateway to university mainframes for loading tools, obtaining access to very large databases, or for computation-intensive calculations. How might such an approach be made feasible at the precollege level?

Research and development issues in this area are complex and deserve much more attention. Some of these problems are technical and engineering issues--such as establishing communication standards that would allow for compatibility of network systems and protocols, making cheaper communication software and hardware, and lowering service costs for greater accessibility to school systems. Other projects are directed toward technical and conceptual problems involved in effectively coordinating information exchange across individuals and groups (90, 119).

Many of the fundamental problems of learning-through-networking have yet to be addressed by the cognitive, social, and instructional science communities. Under what conditions and for what topics would cooperative study, or other cooperative learning activities (such as project-based work), be beneficial? In the past two years, a major new area of advanced research and technology development has appeared that is described as "computer-supported cooperative work" (138, 181). The aim of such investigations is to establish the functional needs of collaborative work groups in business and science laboratory settings, and to create prototypes of the technical infrastructure of tools and operating systems necessary to sustain such activities. Since a substantial body of instructional research has begun to define conditions under which collaborative small group learning is an effective paradigm for education, one direction of research could center on coordinating findings and methods from the business/laboratory communities and the precollege studies. The link to education is that even workgroups in business are involved in learning.

3.4.5. Multimedia Learning Environments

Apart from the microworlds described above, which have yet to be distributed broadly in education, most of the paradigms for educational technologies described are print-based. This may be because print characterizes information environments in schools today. For most instructional activities, minimal use is made of voice, music, and other sounds, or visuals such as pictures and diagrams in books, and filmstrips, slides, or uses of video in cassette, videotape, or videodisc formats--even though these media may be highly effective for learning. The "text-reading eye" has been the primary sensory channel for most education, and yet this is a radical impoverishment, given the senses available from which learning takes place in the world.

This state of affairs will very soon change. Picture the elementary school teacher discussing earth science and plate tectonics with her students, pulling up for computer projection on-line dramatic video clips of volcanoes, student activities centering on an interactive microworld for examining how continental drift operates, and slides of fossil remains from different continents showing the former connectedness of now-dispersed land masses. One student has the idea of photographing local geological strata, another brings in a home video of television footage on volcanoes he thinks might be relevant, and when they return the next day these images are scanned into the classroom archives for other students to use, too. Electronic messages flow between students and from teachers to students on difficulties or new ways of thinking about what is being learned. The students work at their own multimedia composition workstations, revealing what they have learned by constructing and revising their own reports about plate tectonics from these and other materials they can draw on.

While today this scenario might seem fantastical, it may not be by the end of this century. Dramatic developments in the consumer electronics, telecommunications, and electronic publishing industries are rapidly making available low-cost, high quality, and high volume editing and storage technologies for high-speed computer access to high-quality audio and still and full-motion imagery (1, 31, 104, 105, 167a). While we cannot begin to review the momentous changes in sound and image processing, storage, and transmission underway, several highlights must be mentioned. Numerous experts mentioned the importance of carrying out the necessary research in the education sciences to exploit the potency of these multimedia environments for education. And as some ongoing research studies at Vanderbilt using a commercially-available multimedia system (Handy, IBM: 18-20) indicate, students need to be "producers" of multimedia documents and knowledge, not only "consumers," for effective learning to take place. What might the new "multimedia literacy" become, and how might tools and patterns of communication change, in society and in education? And how might such media--already including the use of techniques such as audio-supported, computer-aided reading tools that speak an unknown word when it is selected (122a, 134, 191), and multi-leveled games directed to fostering component reading skills development (70a, 70b) and vocabulary acquisition (127b)--help learners acquire text-based literacy?

The recent technical developments in this field center around CDs, or compact optical disks for mass storage and retrieval of images, text, and sound (104). Each thin, 150-gram iridescent CD can store 550 megabytes of multimedia memory, equivalent to 150,000 printed pages. While CD-ROM is now useful primarily for archival, read-only purposes, read-write media with similar properties are expected to become commercially available in 1990. Related developments in CD-Interactive (9, 27), the new GE/RCA Digital-Video Interactive (DVI: 200), and other technologies should make possible dynamic, interactive multimedia learning environments that can tap vast archives of text, image, and sound for the uses of education. The Palenque Optical Disc Prototype (Bank Street College: 200) shows some of the potentials of the DVI medium in its dynamic mix of talking book, audio-video encyclopedia, and educational movie activities for 8-14 year-olds' home learning about Mayan archaeology, culture, and ecology.

Over 100 CDs are commercially available, including Grolier's 20-volume Academic American Encyclopedia, Books in Print, and replications of various vast databases previously available on-line. Lancaster and other scholars have documented how the paperless society is on the way. How far behind will a paperless education be? The Library of Congress has established The Center for the Book, to explore how changes in information technologies will change the way in which the information in books and other documents will be composed, stored, accessed, and perceived (49). The Library of Congress is putting its vast visual reference materials on CDs, and the Smithsonian Institute has similar efforts underway. MIT is placing its 300,000 graphic works on CD, and art museums throughout the country are investigating opportunities to disseminate compact editions of their collections on CDs. Apple Computer, Lucasfilm, and National Geographic recently announced a joint project to create multimedia educational materials with CD technologies. And in related developments, the entertainment industry, including such movie makers as Warner Brothers, Columbia, Paramount, Lucasfilm, are supporting research and development activities to create low-cost (digital) optical disc movies (132), and interactive television (6a). Even today, (analog) interactive videodiscs of movies are broadly purchased, and the potential interest in home video is revealed by the 40 million videocassette recorders in American homes. Since each CD can store vast numbers of images, local home or school access to image archives will be possible. Network access (167) and copying of imagery onto local storage and replay/editing devices will be a parallel developing activity, depending on how the economics of central storage and access charges is settled.

Particular excitement among educators has been generated by the recent availability of "hypertext" and "hypermedia" systems. Hypertext is an information structuring paradigm designed to match the nonlinear, associative nature of human thinking, which is poorly supported with present linear, text-based technologies (56, 85, 192). In effect, it is the generalized footnote. These complex interdependencies among ideas are particularly evident in documents such as dictionaries, encyclopedias, and training manuals, but they formerly required lots of fingers and thumbs for flipping back and forth between books and book sections (195). Hypertext technologies provide ways of pointing from one place in a text-space to another, and labelling the type of pointers for computer search capabilities. Labelled links forming conceptual maps or "webs" among ideas may be created--in what are called "hypermedia" systems (146, 202)--by students, teachers, and researchers in between text fragments, graphics, timelines, and video clips, to be "travelled" by readers of these hypermedia compositions. These webs of relations can be saved, revised, shared, just as a text or musical piece might be in previous media, creating dramatic new opportunities for providing multiple contexts for learning concepts.

Optical disc storage of text will also be commonplace, with the important exception that information retrieval techniques developed in computer science will provide for full indexing and concordance capabilities, so that entirely new kinds of reading and research activities will be possible with these interactive, multimedia books. Relations among reading, writing, editing, publishing, are likely to change as readers annotate and engage in debates in the electronic "margins" of documents and create communities of interpretation (1, 56). The Brown University experience with their prototype Intermedia software environment in teaching cell biology and nineteenth-century English literature this year has captured much popular attention (202). Faculty consider the rhetoric of hypertext particularly well-suited to promoting the "understanding" involved in multiple interpretations of ideas and their relationships, whether in humanities or in the sciences.

Similar hypermedia R&D efforts at the precollege level in the next decade would provide on-line access to the vast archives of images and sound for education being converted to electronic form throughout the country, including maps, speeches, radio broadcasts, music, drawings, paintings, photographs, and full-motion video and film. The first hypertext product appeared commercially for Apple Macintosh computers this year (Guide), and several others will be appearing in 1987-1988. And there are at least ten different hypertext systems under development in major software, hardware, and research laboratories (56).

Beyond local storage of large media archives on optical disc, network access to images will become commonplace once broadband, fiber optics transmission provides the information gateway served by phonelines today (167). There is a trend to local mass storage, but costs of many CDs are high now because of low volume sales. Industry researchers predict this will change late in this century with fast transmission rates of broadband transmission and the availability of cheap color bit-map advanced function workstations. Electronically delivered magazines and movies, personalized television news and radio (MIT Media Laboratory: 182), multimedia home shopping for consumer goods and real estate, will all provide market forces contributing to the availability of these multimedia information services and technologies. A prototype of such a vast multimedia information service is in development for the Telesophy Project at Bell Communications Research (167: "telesophy" means "knowledge at a distance"--the modern extension of "telephony").

Though it may be several decades before standards are defined for image indexing and retrieval schemes, and until large volumes of graphics and texts become available through these media, research is needed on creating tools so that students and teachers can make effective use of these materials for learning. It is a broad consensus of the information sciences and telecommunications communities that these technologies will become commonplace. But unlike what happened with network television, the educational community should be ready with research that speaks to issues of specific needs for teaching and learning, and which builds on the best analyses of education from the cognitive, social, and instructional sciences. What this will require is prototype development and research activities using these new developments with precollege students and teachers, throughout the different areas of learning. New creative challenges are being faced by writers, artists, musicians, and filmmakers, using these new integrated media, and the expressive dimensions of their union will be under exploration for a very long time. Education science should help lead the way in creative work with these media. Research is also needed on what multimedia manipulation and composition tools are needed for education; including design issues concerning notational languages, text-audio-image editors, and characteristics of integrated tool systems for multimedia composing for communication (Multimedia Literacy Project, New York University). It is unlikely that needed developments for educationally-appropriate, electronic multimedia education environments will emerge from the commercial marketplace alone. But federally-funded research could make a significant difference in the decades ahead.

As one example, we note that all obtainable NSF-funded elementary science curriculum materials created with tens of millions of federal dollars during the 1960's and 1970's (approximately 15,000 pages) have just been made commercially available with indexing software for only $150 (a CD player costs $900-$1000). This disk should provide an important source for research and development activities in science learning to build upon.

There will also need to be technology transfer efforts specifically designated for education, such as the provision of inexpensive digital scanners of text and images, easy-to-use, low-cost videorecorders/ editors for student and teacher use, and low-cost color printers for computer-accessed imagery.

Networking technologies are already making radically different information access possible for the classroom, although such access is largely text-based thus far. One barrier to student access to on-line databases has been that the language for formulating queries varies for almost every database. Now in Einstein (Addison-Wesley), one query language is available for students that enables access to the materials in about 900 databases. Einstein serves as a translating "front-end" to these databases, converting the students' queries in its language to the required format for any of the other databases. But information access does not make education. Students need to know how to formulate inquiries that information search may play a role in, and then to know how to filter and organize the information they obtain through searches in order to address the questions that led them to their initial search. Students will need special browsing tools for examining large information databases designed to take account of features of their understanding and of learning environments (146). Cognitive and instructional research on reading comprehension and writing has focused primarily on single texts (23), and needs to be extended so that we know more how students can learn to synthesize information from diverse sources collected for a variety of purposes. How should searches and inquiries be formulated? What are the information age equivalents to what used to be taught as library skills?

We unfortunately know very little about student learning from even presently available video, film, and interactive videodisc materials (20). Research is needed to guide educational practices for when such media are helpful, under what conditions, and for what topics. Good education does not always require broadcast studio quality, and some research indicates that for some learning objectives, line drawings may be superior to pictures (which include many instructionally-irrelevant details. We also need to investigate how to utilize the interactive potentials of computers to design interactive or "smart" pictures, graphs, and diagrams, that can explain themselves to students, depending on answers students give to questions posed by such visuals (93a). More intelligent and consistent methods will need to be developed for indexing, retrieving, manipulating, and editing images, sounds, text, and other data from mass storage media, particularly if they are to be accessible to students and not only teachers. Previous work on standards that has led to acceptance of user-interface protocols, such as the Apple Macintosh's "cut and paste" editing methods, needs to be extended for integrated multimedia environments and for educational users.

3.5. Changing How We Track Learning

The research in the cognitive and instructional sciences on the nature of "understanding" we earlier described has profound implications for how the educational establishment tracks learning and measures developmental progress in achieving educational goals. At present, very little school assessment is directed toward diagnosing students' conceptual understanding (71, 77). These issues are not only critical for improving education. They are also important from an economic perspective, since determining the quality of the content or the design of an educational technology cannot be determined solely from inspecting it. From a policy perspective, we need measures of the impact on learning outcomes of an educational technology (under specific use conditions). These measures should match what cognitive research on "understanding" indicates to be the objectives of education (25, 28, 113, 177b).

But to achieve this goal, major changes are needed in prevailing methods for learning assessment. A National Research Council committee report states that: "Tests also play a role in the learning process itself. They tell students what in the curriculum is important and shape the teaching and learning process....If, for example, testing is confined to memorizable end results, students will concentrate on these end results, ignoring the more sophisticated levels of understanding and reasoning to which teachers and test makers may be rendering lip service" (120, p. 25).

On one extreme, theorists argue that we need to devise assessment strategies that check for the attainment of nontrivial skills (153, 166). They suggest that particular attention should be paid to "complex thinking skills," such as the ability to generalize appropriately, to invent analogies and use them critically, to decompose problems into interacting parts, to effectively manage and deal with complexity, to lay out a procedure as a sequence of approximations which converge to solution, to analyze a situation from a viewpoint other than one's one.

One the other extreme, theorists argue that we cannot expect to be able to measure such general capacities, since they may be developed distinctly in each substantive domain of learning (44, 76). They suggest that we may make assessments of one's level of progress in conceptual development for each subject domain of interest, based on empirical data studying the course of individual learning in that area. Assessment in this case is tied to theories of conceptual development, and stages of task proficiency. Both orientations consider today's item assessment tests inadequate as measures of understanding or skills. Finally, many empirical analyses imply that learning to engage in self-evaluation as one is learning, for example, testing one's comprehension in reading or in acquiring new ideas in science, and strategically working to overcome learning difficulties, should be educational priorities (23, 51, 125, 153, 170).

A substantial body of research findings on students' experiential learning outside school indicates that students often have alternative conceptual frameworks that constitute "preconceptions" from the perspective of formal learning, and that run into conflict with traditional instruction that does not recognize the potency of their previous beliefs. There is substantial evidence, for example, of the superficiality of student understanding of force and motion after instruction: they demonstrate misapprehensions in qualitative reasoning about the same situations that they can set up and solve formal equations for! Such curricula do not prevent everyone from understanding science, but it is widely conjectured in the cognitive research community that a much greater proportion of students would learn science with understanding if we tracked learning and taught with awareness of these alternative frameworks (25, 33, 58, 120, 142). Since the cognitive and instructional science research studies indicate that we need to teach to the student's present level of conceptual understanding, teachers need better diagnostic instruments for ascertaining what students believe about what is being taught. They also need more refined developmental theory of subject matter understanding than presently available to guide instructional interventions, and uses of technologies, once one has an accurate knowledge diagnosis.

For these reasons, a substantial federal investment should contribute to the creation of new research-guided precollege curricula, coupled to new assessment instruments for measuring deep conceptual understanding and diagnosing prior understandings.

3.6. Changing What's Taught

The cognitive shift in education provides the foundation for calls of curricular reform from the research community. Thus, we now know that our central goals in education are to have particular knowledge structures represented in students' memories that ensue in appropriate action, and that capturing subject matter knowledge structure in the curriculum to be taught is insufficient. *The reason is that knowledge is not "transmitted" by education, but constructed by learners from educational activities in relation to what they already know.* Key attention is paid to analysing students' alternative conceptual frameworks for reasoning about the topics they are being taught, and whether they are making progress toward the formal understanding of subject matter knowledge represented by the mature field. A rigid following of curriculum guidelines can ignore what students might want to know to help them in learning.

This cognitive shift has major implications for what should be the nature of curriculum, and more broadly what is taught in education. Under "what is taught," we include not only the textbooks, teacher lectures and demonstrations, and activities such as reading, working problems, and class discussions which constitute the bulk of instructional interactions used in schools, but also the enrichment activities, such as movies, videos, field trips, and laboratory experiments, that are adjuncts to the main content of a course.

Below we note the major observations that have arisen as consensus points in the cognitive and instructional research scientific communities, so that students learn for deep understanding rather than surface proficiency in recalling facts and formulas and symbol manipulations. We then present research and development activities suggested by the experts we consulted as means for closing the knowledge and technology gaps.

Too much is being taught to be learned for understanding. One of the most important lessons of cognitive studies of subject-matter learning is that teaching for understanding is much more demanding of classroom time than present instruction, which teachers literally need to race through to "cover everything" (116, 120). And the breadth of this "coverage" continues to accelerate as otherwise well-meaning subject matter organizations, such as the American Chemical Society (187), or the American Physics Society, recommend including yet more topics in the precollege curriculum. But "less is more" when conceptual understanding is the aim of educational activities. This conclusion was reached in a 1986 research agenda planning workshop at University of California, Berkeley and Lawrence Hall of Science (116: funded by NSF) in which forty-five mathematicians, scientists, cognitive scientists, mathematics and science teachers, and curriculum and technology experts participated. *But deciding what central topics need to be taught for understanding will depend on what we consider to be the tasks at which students need to do well.*

To take but one example, an interdisciplinary group at Harvard's Educational Technology Center has after three years of research devised a one-month unit, using educational software and novel teaching methods, that is highly effective in leading ninth graders to understand the heat-temperature distinction (201a). This is a conceptual hurdle for precollege science, and since it is the first time energy is treated, it is intimately related to understanding the molecular model of matter, and thus a focal part of any science curriculum. But only 5-6 days typically is allowed to cover this topic.

New curricula must recognize the existence of students' alternative conceptual frameworks and be responsive to them. Curricula need to be developed that not only present appropriately structured subject knowledge, but materials that address known preconceptions students have for the subject matter to be learned. There is a great deal of research identifying alternative conceptual frameworks students have in science (32, 33, 38a, 39, 40, 58, 60, 61, 74, 106, 116, 177b, 122, 123, 142, 193, 194, 201). But we know far less about how to provide instruction that would enable students to construct new understandings reflecting the structure of modern knowledge. Large-scale research and development projects should address these concerns systematically for major chunks of central curricular topics. Once students' alternative conceptual frameworks for each curricular area are reasonably well-specified, the use of knowledge representation languages and artificial intelligence methodologies might be used to help automate the process of diagnosing a student's current conceptual framework. We also know too little about how experiential activities prior to schooling contribute to the formation of students' alternative conceptual frameworks; yet such understanding could help guide the design of new learning environments for promoting conceptual change toward the formal standards of subject understanding conveyed in school (89, 116).

Functional learning environments can be designed to narrow gaps between knowledge acquisition and application settings in society and in education. As earlier discussed, the acquisition of new learning in performing whole tasks (such as newspaper writing/editing, research in social studies or science, or applied mathematics) under the guidance of more able peers or a teacher can connect school learning to real societal contexts. Technologies can play key roles in this process, and the feasibility of widescale implementation of existing prototype efforts with this orientation should be examined.

We must systematically examine how technologies can make higher learning and complex thinking more accessible to more learners. Curricula need to change to reflect what it is possible for students to do and understand with new technologies. We have heard frequent references to the "complexity barriers" involved in learning formal topics, particularly in mathematics, sciences, and technology (62, 94, 98, 116, 171, 190). It is the belief of many researchers and developers of educational technologies that many of the features of such complexities are media-specific, and that new learning tools can overcome them. More extensive research and development collaborations with this theme need to take place between professional educator organizations in the subject disciplines and the education science community. Innovations are slowly appearing in which calculators and computers play integral parts of student activities in existing curricula (116, 120), but much more comprehensive and innovative efforts will be required. Three major directions of curricular tools, building on research earlier described, were commonly mentioned as bearing great promise in this regard.

The first is crafting learning environments with multiple representations of knowledge whenever possible, since multiple ways of knowing may make a topic more accessible to certain learners. If possible, such representations should be linked so that the learner may establish intuitive understanding of how changes across the representational media are related (97, 154a). Software environments with these properties are under development for reasoning about intensive quantities (ratio, proportion) and algebraic modelling at Harvard's Educational Technology Center (65a, 97), and for modelling systems dynamics (TERC/Lesley College: 190). The *Boxer* programming environment (U. California, Berkeley: 63) will provide students with linked program outcome and control program representations that are now finding their way into professional programming environments. Many more topic areas could utilize this approach, and research examining the conditions of its effectiveness for learning is an important need.

The second need is deeper understanding of the role of visual representations, of pictures, diagrams, graphs, flowcharts, and other non-text media in learning processes. Random access videodisc and compact optical offer much more provocative but little understood educational possibilities than linear videotape. The need for research understanding of how such representations function in the learning and reasoning processes of students is particularly critical because new information technologies provide opportunities for much greater exploitation of non-text media. Object-oriented graphics editors, digital scanners for photos and video frames, and animation tools, are available at reasonably low cost for computers in the $2000 range, and are being used for these purposes in learning technology development work (1).

The third need is for programmatic R&D efforts to provide new materials that allow the linking and co-articulation of subject matter understanding across now-isolated curriculum areas, so that students will remember and use task-appropriate collections of understandings to solve real problems--which researchers find rarely respect the curriculum boundaries established in school. Project work at Vanderbilt University with this emphasis, using existing interactive videodisc technologies under microcomputer control for promoting integrated learning of mathematics, science, and reading, has resulted in promising learning outcomes for at-risk middleschool and elementary students (18-20). A particular priority and opportunity with this emphasis would be creating learning environments for discrete mathematics and statistics--for which there are essentially no texts and no teachers at the precollege level--even though these have become critical topics for students to understand as they enter college.

In contrast, we found that experts consider curriculum reforms designed primarily to "keep pace with the information explosion" to be unrealistic. While some have argued that the main need for curriculum reforms is the pace of knowledge change, which requires new and up-to-date texts and curricula, it is clear that such an emphasis, relying as it does on a "knowledge transmission" metaphor for the role of education, is fighting a losing battle. There is no way to keep pace, so a growing recognition is for the need to teach generative learning skills, exercised against the best available substantive materials, with clear recognition and communication to students that knowledge will continue to change. Educators should also stress the acquisition of productive inquiry skills so that students can find and reconfigure needed knowledge for their own purposes, rather than having information stuffed into their minds at a faster and faster pace.

3.7. Changing What Teachers Do

Research in the cognitive and instructional sciences earlier described on the nature of teaching and learning has major implications for what the activities of teachers should be. (Since another OTA subreport will deal centrally with such issues of teacher education and educational technologies, we will not focus on them here.) But several points deserve special mention. The statistics available paint a bleak picture for the teaching profession. We have heard expressed particular concerns about the low levels of teacher certification in mathematics, science, and English; the lack of subject matter understanding even among many of those certified; the drop in numbers of new teachers being educated; the lowering SAT scores of teachers entering the profession; the high rate of forthcoming teacher retirements; and the poor image of career opportunities many teachers profess (93).

Technology has a curious but intriguing role in this picture, and unfortunately, little research is available that will help guide decision-making about it. Many different roles were described for the teacher-technology relation (116a). Only a few of the experts we consulted described the preferred role of the technology to be directed at *replacing* the teacher. Some believe that this is what "intelligent" tutors are being designed to do, but the general belief was that relatively little of formal education can be mechanized in that fashion.

Most experts instead highlighted the ways in which the computer can be used to **revitalize** the teaching profession in many ways (93, 116a, 203), including: (1) providing better education to teachers about the incremental change (rather than all/none) nature of the development of subject matter understanding, and teaching pedagogical methods for diagnosing students' preconceptions so that they will better be able to know where students are in the learning process; (2) changing teachers' roles and making their work more interesting--in particular making their role more one of "coach" than delivery agent of learning (the assumption being that small groups or individual students can focus on thinking and problem-solving through the use of such tools such as micro-based labs, microworlds, word processors, and database programs); (3) promoting more effective learning of subject matter, reasoning skills, and pedagogical methods through uses of the technology itself, through in-service, pre-service, and networking activities. Perhaps the greatest satisfaction of all for teachers, if present research understanding finds its way into practice, will reside in providing students with better understanding than they have before. And while few now believe that computers will necessarily make teachers' lives easier, they may make their work much more interesting and challenging intellectually.

Our experts consider a focus on teachers to be essential. As one research scientist assessed the present state: "The problem with education now is not what *students* are capable of, but what *teachers* are capable of, given their previous education. There is a general consensus, at least in science learning, that teachers need to teach to students' conceptual understanding. Students interpret curriculum in terms of their preformal conceptual frameworks. The major problem of educational research and development is to educate teachers about this consensus view, and in how to diagnose students' alternative frameworks for thinking about what is being taught" (Dr. Susan Carey, MIT).

3.8. Changing the Schooling Environment

Research from the education sciences revealing the influence on learning of the social context and schooling environment has major implications for designs of school learning environments. Some directions considered promising for change are those in which teachers teach partly by modelling thinking processes (e.g., in reading comprehension) and engaging students in "cognitive apprenticeships," in which an environment is created for promoting students' positive self-images as learners, and in which peer collaboration and tutoring, and small-group learning are encouraged (51, 52, 153, 154a). But these opportunities are poorly understood at the present time in relation to technologies, even though they are integral to effecting school change that builds on research knowledge. For this reason, new empirical studies are required. Research and technology development activities at this level of analysis, which has been described as "microsystems," simultaneously studies the social organization of instruction and curriculum content (120).

Technologies may have a special role to play in the future of microsystems research. Networking technologies would fundamentally change the communication systems of classrooms, connecting teachers and students to other learning and teaching resources, both human and information databases. Telecommunication technologies such as major networks and local-area networks (LANs) are currently cumbersome and costly for schools to implement. The importance of the planned NSF support for developing high-speed, high-bandwidth compatible national networks to replace the present Arpanet system has been aptly described as providing the information equivalent to the interstate highway system. Smaller-scale but parallel federally-initiated efforts should work at the school-level, and could solicit complementary local and state education funds for this purpose. Research and development efforts are needed that aim for cheap, compatible networking hardware and software to support collaborative project work and cooperative learning activities within and across schools, and access to information databases on-line. Such work would require basic studies of human-computer interaction for student-appropriate interface designs (71a). Satellite transmission of educational materials also requires careful study, but it is important that the cognitive shift in education outlined throughout this report be reflected in experiments involving this technology.

While these telecommunications may dramatically expand the learning and teaching resources available for students and teachers, some concern has been expressed that the communication infrastructure of schools is vastly underdeveloped to support these changes: since so few classrooms have telephones, how likely is it that they will support costs of modems, local-area network cabling, networking, and satellite transmissions?

Staffing Levels and Cost for a CITE Per Year

[1]Senior Staff	5	$200,000	$1,000,000
[2]Support Staff	35	100,000	3,500,000
Post-doctoral Fellowships	10	100,000	1,000,000
Visiting Faculty	10	100,000	1,000,000
Graduate Fellowships	10	40,000	400,000
[3]Staff to work with school teachers	13	100,000	1,300,000
[4]Equipment/School/Hardware per student	390	3,000	1,170,000
Equipment/School/Software per student	390	500	195,000
[5]Equipment/School/Hardware per teacher	13	4,000	52,000
Equipment/School/Software per teacher	13	2,000	26,000
TOTAL			$9,643,000

Cost of Phase 1

Year 1 (2 CITEs)	19,286,000
Year 2 (1 New CITE, total 3 CITEs)	28,929,000
Year 3 (1 new CITE, total 4 CITEs)	38,572,000
Year 4 (1 new CITE, total 5 CITEs)	48,215,000
Year 5 (1 new CITE, total 6 CITEs)	57,858,000
Year 6 (6 CITEs)	57,858,000
Year 7 (6 CITEs)	57,858,000
Year 8 (6 CITEs)	57,858,000
Year 9 (6 CITEs)	57,858,000
Year 10 (6 CITEs)	57,858,000
Total for all CITEs	$482,150,000

TABLE 1.

---

[1] Of the $200K per senior researcher, approximately $80K goes for salary, while the remaining $120K goes for "indirect costs" and equipment. This level of "burden" is typical of active research and development environments.

[2] Of the $100K per researcher/developer, approximately $40k goes for salary while the rest goes for indirect costs and equipment.

[3] There will be one resource person assigned to each grade (class) in the CITE school whose explicit role will be to facilitate the back and forth transfer issues associated with using the technology in the classroom.

[4] We estimate 30 students per class for each of 13 grades (classes).

[5] Each classroom teacher needs to have a modest hardware (and software) budget.

3.9. Other Needed Research and Development Activities

Several priorities were described which do not fit well in the categories outlined above, because in an important sense they involve all of the categories.

Comparative research evaluations are needed of different approaches to the same instructional task to test the strengths and weaknesses of different learning theories. Several experts suggested that present development environments for the programming of prototypes of education technology such as InterLisp-D/LOOPs (Xerox PARC: 13) or Boxer (U. California, Berkeley: 63) would allow graduate students to do this in a semester. Implementations would be tested formatively (for interest, comprehension), summatively (for learning outcomes), and in terms of the quality of the revised learning theory generated. More graduate students, hardware, and laboratory schools would be required to do this any more broadly than at two or three research-oriented laboratories (e.g., U. Pittsburgh, Berkeley, Carnegie-Mellon).

A cluster of other important issues centers on establishment of standards, compatibility, and R&D that would contribute to improving production economy for educational technologies.

Standards in interface design are needed to reduce for teachers and students learning time and to ensure compatibility for cognitive workbenches such as text editors, drafting programs, theorem proving assistants, algebra assistants, outlining tools, spreadsheets, graph plotters. Additional work on interface conventions for accessing/storing data that would be readily accessible to, for example, elementary school children will be important. (Much like what has occurred in the acceptance even by IBM, in their new Personal System series of computers, of Apple Macintosh interface conventions such as files-as-icons, multiple windows, and pull-down menus). These developments are not likely to take place in the commercial arena because of the lowprofitability of educational technology materials, but will be critical for education.

Helping reduce costs of producing technological media is another goal mentioned by experts as an appropriate federal role (28, 126, 159a). For example, "courseware" development, as defined by sharp domain boundaries and clear sequential strategies for instruction, is often provided, particularly in commercial and military training applications, by instruction-controlled videodisc, videocassettes, intelligent tutors, which are highly expensive. It has been observed that typical expensive production methods, coupled with keen commercial competition, has resulted and will continue to result in poor quality instructional goods. This problem also exists, but to a lesser extent, for the costs of courseware production involving more flexible browsing/resource systems (CD-ROM, databases), where many activities are locally adapted and not specified at great levels of detail since they are under greater user control.

Two strategic approaches may meet this problem of costs (159a). One involves lowering development costs, the other improves the analysis /evaluation of instructional products. These approaches are in contradistinction to the present trends of increasing the effectiveness and variety of such educational media.

Lower development costs and more efficient production would be likely to arise from better theories of learning, since empirically-grounded principles would lead to better first prototypes, and instructional development costs are dramatically reduced by how good a version of a product one begins with in testing. Such an objective calls for basic learning research aimed at facilitating effective instructional design and intervention, and increasing our capacities to assess competencies in knowledge domains. Without goals for educational products, drives for more-economic development are aimless. As discussed elsewhere in this report, present testing measures are inadequate to these purposes, since they do not provide the needed instructionally relevant observations about a learner's level of understanding and skills, and qualitative observations of student performance are insufficiently rigorous. We are in particular need of such methods for determining competence in the broadly taught school subjects, and their availability could have critical impact on the quality of teaching and learning, and the design and production of instructional technologies.

The other strategy aims at reducing costs of both the synthesis of educational technology materials. As for synthesis, there are high costs associated with gathering and extracting information--textual and graphical--required for design of instruction. This activity is often underemphasized since reference materials are considered to be widely available for presently taught school subjects. Requisite tools include those for automated indexing, and AI-supported information retrieval methods. Substantial basic research on techniques for effectively indexing and retrieving graphics are needed. Instructional designers would often like information menus for choosing content, and readily-reconfigurable databases devised for these purposes could also be used by teachers for preparing lessons, and for students in research activities and report preparation. A related goal is to develop highly-automated camera and videorecording/editing equipment, so that urgent educational problems may be met creatively by teachers without the over-emphasized (from a pedagogical perspective) broadcast production aesthetics of present educational video.

4. Policy Suggestions: Plans for Revitalizing American Education

In the foregoing, our primary intent has been to describe in the somber tones of academic prose the advancements in education science and technology that presage fundamental changes in education. However, our intent is also to generate genuine excitement for a vision of the future where education is a vehicle for empowerment; where learning is exciting, stimulating, fun; where kids are active participants in a profoundly important individual and social ritual -- that of idea creation and idea interchange. For example, consider the following technological products that are literally just around the corner:

> Doing history, not just reading about history: Developing interpretations for events is a key activity of historians. Imagine, then, that you are trying to understand the influence of various paintings on the writings of Robert Browning. You can select a piece of Browning's text, and call up --- on your computer screen --- the paintings that Browning was thought to have known about. You then piece together an argument on "influences": the golden color of the wheat in this painting appears to be reflected in this poem, and so forth. However, given the uncertain travel arrangements -- which you get by looking at travel documents, also on your computer screen -- it seems unlikely that Browning could have seen the painting before he wrote the line. And so on. Without the computer, this historical investigation would either have been impossible or highly problematic--- especially for a student in a rural school nowhere near the primary sources.
>
> Doing science, not just reading about science: Acid rain is a hot research topic in science today. A rich corpus of data is going to be crucial to pin down exactly how this phenomena works: there are surely multiple lines of causation and interacting factors by which acid rain occurs. What if 25,000 students collected data on this topic in different regions of the country, and collected data on various environment factors, e.g., the amount and type of industry

in the area, numbers of smokestacks, and so on. And, what if these students were able to put these data on-line, so that all 24,999 other students might have access to it for analysis, for on-line discussions of the trends, and to spur further research. And, what if data analysis tools were available, and simulation programs to model acid rain's effects. It is not implausible that some students may develop fine conjectures and scientific explanations for aspects of the acid rain problem: the data and the analysis tools accessible by the 25,000 students are comparable to that accessible by a "true" bench scientist. Who is the real scientist now?

Doing art, not just reading about art: Everyone at one point or other dreams about being a movie producer. Talent aside, the logistics prevent all but the most motivated to get a chance. However, through the use of "video design programming languages" and electronic networks tied to databases of video-images, students can create their own personalized videos --- while sitting at their desk.

The above vignettes are not blue-sky, wishful thinking: education science and technology has developed the theory and the technological base for creating these sorts of dynamic educational products. In fact, each of the above are in the prototype stage now.

What are called for, then, are mechanisms through which a systematic multitude of vignettes of the above sort can be realized. More generally, mechanisms are needed by which the broad, but focused changes described earlier, in what students do, how they are taught, etc., can be brought about. What should be the federal role in developing and nurturing such mechanisms?

In this section, then, we present three alternative courses of action for the federal government.

Option 1: Significant increase in Federal spending. In this plan, we call for the creation, over a 10 year period, of 6 major Centers for Interactive Technologies in Education, plus the need for a substantial increase in funding of individual researchers.

Option 2: Modest increase in Federal spending. In this plan, we call for the creation of only 1-2 centers, with only a minimal increase in funding of individual researchers.

Option 3: No increase in Federal spending. Under this option, the federal role would be as it is now. The burden of furthering education, then, would fall to the private sector.

We go on to assess the effectiveness of the mechanisms in each of these options with respect to the following four goals for educational vitality emphasized by many of the experts we interviewed. The achievement of these goals will provide the basis for the wide-ranging, deep changes we indicated earlier were beginning to take shape:

Goal 1: Producing and exploring new ideas in education science and technology. Our storehouse of ideas in education science needs considerable expansion. We need more deep theories of learning, teaching, understanding, expertise, etc. Moreover, we need to explore these ideas in a systematic fashion. Under the current environment, researchers must often drop a line of inquiry due to the vagaries of funding without an adequate assessment of its potential. Still further, we need to develop ways to quickly, and cost effectively, prototype and evaluate technological innovations.

Goal 2: Developing an extensive community infrastructure. Work in education science is inherently multi-disciplinary, and labor-intensive. Simply put, we need a major influx of talented individuals who are committed to doing something significant in the field. We need to provide clear avenues for the development of first-class researchers and developers.

Goal 3: Providing professional development opportunities. High on the list of priorities must be ways to involve the classroom teacher more actively in all phases of innovation: from idea conception to research, product development and evaluation, teachers need to be involved as first-class citizens. A plan of action that does not allocate a substantial portion of its budget to "in practice" issues will not result in the changes we described earlier.

Goal 4: Producing and disseminating technological products. The cost of developing high-quality, educationally-principled technological artifacts is high -- and the return on investment may well not be there. This is a plain fact that educational software houses and publishers, for example, know only too well. Creative strategies need to be developed to support commercial concerns, while not unduly constraining researchers' imaginations. Current modes of marketing and distributing technological products are both costly and oftentimes ineffective. Again, strategies need to be explored that bring products to the public in a timely and affordable manner.

In what follows we examine the potential of each of the three options for achieving the above four goals.

4.1. Option 1: Significant Increase in Federal Spending

This first option has a 10 year duration, with three overlapping phases:

Phase 1: Establish Infrastructure -- create Centers for Interactive Technology and Education (CITE) where research, development, dissemination, and evaluation take place in a realistic learning and teaching situation.

Phase 2: Begin Dissemination to Public Schools -- facilitate active commercial distribution of the CITE products, and develop the baseline technologies that will enable teachers and students in the schools to have nationwide access to products, information bases, etc.

Phase 3: Accelerate to Nation-wide Dissemination -- provide access for every school to a Resource Center that can assist teachers in integrating the ideas and technology from education science into their classrooms.

This option is based on: (1) our analyses of effective organizational structures in comparable fields (e.g., biomedical engineering) and (2) on recommendations from the experts we interviewed. For example, almost universally, our experts stressed the need for nationally sponsored centers that would bring together a critical mass of people, with ideas, talents, and skills, to work on the complex, important problems in education. Moreover, essentially all the previous reports on policy recommendations have suggested comparable mechanisms (25, 112, 113, 116, 120, 121, 131).

Phase 1: Establish Infrastructure. There are two major thrusts to be accomplished during Phase I:

* Develop Centers for Interactive Technologies in Education

* Increase support for individual investigators as well as provide supports for commercial enterprises that are involved with educational technology.

Centers for Interactive Technologies in Education

A major innovation proposed is the establishment of 6 Centers for Interactive Technologies in Education (CITEs) across the US, over the next five years. Two centers would be established in Year 1, while one center would be established in each of the 4 succeeding years (of Phase 1). Each CITE would be intimately tied to both a K-12 school system and a major research institution. There would be two major functions of each CITE: (1) conduct both basic research in education science (the cognitive, social and instructional sciences), and (2) carry out development and dissemination of technological products. In addition, each CITE would have the following sorts of functions:

holding workshops for teachers in the CITE-associated school and for other teachers and educators in the area,

hosting visiting faculty and post-doctoral fellowships,

providing research/development facilities for graduate students, disseminating the CITE developed products on a large-scale, e.g., interact with commercial enterprises for the marketing and support of technological products.

As detailed in Table 1, the cost of one center, when equipment and support personnel are added in, is estimated to be approximately $10 million per year. This figure is higher than that typically associated with centers (e.g., Learning Research and Development Center at the University of Pittsburgh, or the Educational Technology Center at Harvard). However, as we briefly outlined above, a CITE would be a much larger enterprise than are the current centers. However, as Table 1 clearly shows, close to 30% of a CITE's support goes for "in practice" support: providing the children and teachers in the attached school with hardware and software, providing staff to work with teachers and schools in the region, and providing support staff of for the dissemination of the CITE-developed technological products. These functions are not a major part of any current center; by and large these functions just aren't being carried out.

Each CITE should be located at a major center of research. This model is one that is currently being employed (e.g., the Educational Technology Center, is located at Harvard.) Moreover, to foster both synergy and diversity -- and to create a critical mass -- we propose that a CITE be composed of 5 senior researchers and a staff of approximately 50 associate researchers and developers. (In addition to full-time staff personnel, research and development groups will draw on visiting faculty and CITE-sponsored graduate students.) The 1:10 ratio is one that is common in productive research laboratories. Thus, a CITE is a major institutional structure.

We propose that the CITEs not be chartered to focus on particular curricular topics, particular grade levels, or particular technologies. Rather, we propose that CITEs be encouraged to explore the full spectrum of topics, grade levels and technologies. The multi-media, interactive technologies actively facilitate the crossing of subject boundaries. In the "acid rain project" cited earlier, writing, communicating, and mathematical skills arise naturally in the context of the scientific research that the students are carrying out. And numerous experts consider grade-level accessibility of complex concepts and skills quite malleable with computer technology supports.

Following the guidelines for the new NSF centers, and for other comparable institutions (e.g., MCC in Austin, TX), the cost of a CITE would be borne in part by the federal government, and in part by private industry. A commercial concern would buy in for a share, and have access to various center resources. Similarly, DOD would be encouraged to participate in the CITE program. While the details need to be carefully worked out, the point is that such joint federal-commercial funding relationships have recently been found to be effective, and thus we have reason to believe that such an arrangement would work in this area also.

With that brief description of the functional architecture of a CITE, let us now assess the utility of a CITE with respect to the four goals identified earlier as being critically important for revitalizing American education:

Goal 1: Producing and exploring new ideas in education science and technology.

Support the integration of research and development. Over and over again, our experts made strong recommendations that theory must not be divorced from practice. That is, the most common model of research and development is that research constructs a theory, hands it off to the developers, who then make it into a product. However, this model of the relationship between research and development has not been an effective one in education. Rather, education must be viewed more as an engineering discipline than as a pure science: in education, theory must lead to products, feedback from which helps to reshape theory. In what follows, we sketch four reasons why the CITE model in Option 1 puts significant emphasis on facilitating the integration of theory and practice.

First, theorists need to study real phenomena: the phenomena under study in the cognitive, social, and instructional sciences do not lend themselves to "laboratory study," where small, isolated components are studied and for which circumscribed theories are constructed. Theories of nonsense syllable memory, while permitting controlled experimentation, simply do not scale up to realistic learning situations. Rather, laboratories for developing viable theories of learning and teaching are just the naturally occurring learning, teaching situations themselves.

Second, developers need a direct channel to researchers, since realizing complex theories in an educational product requires considerable interaction between theorists and developers. The costs of producing technological products can be dramatically cut as a result of the close collaboration between researchers and developers. In particular, armed with better theories, the developer has a better chance of developing a more effective prototype the first time around. Without such a theory to use as a guideline, one is surely less confident that what one initially produces will be at all useful.

Third, there must be a direct link between the researchers/developers and the school teachers, who ultimately have the responsibility for employing the developed technology in the classrooms. There are a number of reasons for the need of this direct link. For one, teachers need to be integrated into the process of educational technology research and development, from conception to final product delivery. Second, education is like the fields of medicine and engineering: new ideas and products are constantly being produced, and thus medical professionals and engineers need to be life-long learners about their fields. Similarly, teachers need to contribute to and be kept abreast of new developments. If such inservice interchanges are integrated into the research and development laboratories, then the lag time between an idea and its dissemination is considerably shortened. Moreover, the critical feedback by the teachers can provide key insight for the researchers and developers.

Fourth, since, as we argued earlier, education is exceedingly complex, education science researchers are often quite surprised by the interaction that results when students meet theory-motivated, technological products. Researchers may need to substantially change their theories, while developers may need to substantially change the design of their products. In sum, then, we feel that the organizational structure employed in bio-medical and bio-engineering research is an appropriate one for educational technology research: there theory and practice are integrated in an effective synergy.

Support for the sustained interaction of colleagues from many disciplines. Research in education science is inherently multi-disciplinary; the production of insightful theories and effective technological products requires the active participation of psychologists, educators, computer scientists, anthropologists, sociologists, graphics designers, subject matter experts, video producers, human-factors specialists, etc.

Provide a rich source of technology for experimentation. Technology creates new possibilities; what can be done with technology often outstrips what people believe it is possible to do. Researchers and developers in educational technology need to have access to a wide range of technologies; they need channels into the manufacturers for experimenting with the latest equipment. While it may take time for the latest technological innovation to percolate down to the schools, nonetheless, researchers and developers who have access to the latest in technology can plan an orderly, effective transition between what is now available and what will be available. In addition, the technology often permits the researcher and developer to do things that couldn't be done before: the technology opens up whole new avenues. For example, CD-ROM permits an individual to literally have at his/her fingertips as much information as was available before in a small library. Given that this enormous amount of information is now available on immediate demand, we need to rethink how information needs to be organized, so as to facilitate the cognitive processes of information search and utilization.

Goal 2: Developing an extensive community infrastructure. In order to insure a sufficient number of researchers and developers to reach a critical mass in education science, adequate training environments and career paths must be provided. While there are schools of education, the majority of research in the cognitive, social and instructional sciences is taking place outside schools of education, by isolated investigators working in the traditional departments of psychology, anthropology, sociology, mathematics, computer science, or small to medium sized laboratories of research and development. Those disciplines have their own well-established methodologies, evaluation criteria, career paths, etc. Oftentimes there is conflict between the traditions of a discipline and the goal of producing theory and product in education. For example, if one is a graduate student in computer science, working on a Ph.D. in artificial intelligence, the objective must be to produce something acceptable to computer scientists, not to educators. Thus, concern for education must remain secondary in these traditionally-structured departments.

In contrast, CITEs can provide a "home" for researchers and developers to contribute to education science. A CITE offers the setting in which training of individuals can be effectively carried out. Moreover, given the proposed extended life span of the CITEs, it would be a reasonable place for career satisfaction and advancement.

Goal 3: Providing professional development opportunities. It is critical that classroom teachers become involved in ideas and developments of education science and technological innovations. In line with our emphasis on integrating theory with practice, CITEs can provide an excellent environment for teacher professional development. CITEs, as part of their basic charter, should run a wide range of workshops and courses expressly designed for classroom teachers. CITE researchers and developers will be encouraged to involve classroom teachers during even the earliest phases of their projects. Thus, teachers will be linked into the new ideas at all levels: from basic research to dissemination and use.

Goal 4: Producing and disseminating technological products. All too often researchers and developers ignore the significant costs and talents involved in successfully marketing and distributing a product. One-of-a-kind deals between publishers/software houses and researchers/developers just don't offer any economies of scale. CITEs can expressly be designed to provide a continuous stream of products for the commercial sector. This continuity of product availability makes it worthwhile to establish high-bandwidth, long-term relationships with commercial enterprises. In turn, these serious relationships will cut down on the unconscionable delay that now exists between conception and realization: there will be a clear, well-defined, well-oiled path from idea to utilized products.

In sum, then, the CITE model seems like a good candidate mechanism for achieving these critically important goals.

In the above discussion, we have highlighted the "pros" of the CITE strategy. We now turn to addressing specific "cons" that can, if not dealt with explicitly, detract from the effectiveness of the center concept:

> There is a danger that centers will lose their innovativeness. Key to lessening the chances of such a loss will be mechanisms that provide for renewal and for interaction with other CITEs, individual researchers, and organizations. For example, CITEs should explicitly rotate their staff through other CITEs: this mechanism will help

> to spread good ideas, and to provide infusions of new ideas. Also, we suggested that CITEs not necessarily be mission-oriented; the senior staff, as well as the associates and teachers themselves should provide a drive for innovation and diversity.
>
> There is a danger that there will be conflict between a CITE and its host institution or other institutions in the field. For example, there is a concern that CITEs will swallow up research personnel; non-CITE universities may not be able to provide an attractive enough environment. Staffing is a problem: there are presently not enough qualified individuals to populate CITEs and universities. However, there is good reason to believe that staffing problems will lessen: CITEs will be major training grounds, and increased recognition of the importance and support of education science will result in its ability to draw high-quality individuals into the field.
>
> There is a danger that support for CITEs will become unduly influenced by political, regional, administrative, etc. considerations. Channeling significant resources to CITEs (and individual investigators) will naturally attract attention. One of the functions of a CITE is dissemination: such an activity will provide the basis for informed decision-making.

In sum, the center concept is not without its risks. Nonetheless, the demand for centers was almost unanimous among the experts we interviewed. Thus, the risks were deemed well-worth the undertaking: the benefits of centers outweighed the risks. Given the importance of centers, it is definitely worth the effort to find ways to minimize their drawbacks.

Our suggestion for six CITEs is based on a number of factors. First, our experts repeatedly spoke of the need for a diversity of ideas: a few CITEs might well not provide enough material in the gene pool, so to speak. Also, our experts spoke of the power of synergy arising from a critical mass of top-flight workers interacting. While CITEs may each have different theoretical stances, interaction among CITEs will expressly be fostered. Second, the commitment of significant resources, in terms of a substantial number of CITEs, will have its own impact on various fields and individuals. It is our sense that once world-class scientists and scholars see that America is serious about dealing with education, they will come and join, even if just temporarily, in the work of a CITE. The contribution of these individuals will be significant. Students will then be able to experience the excitement of dealing with the frontiers of knowledge first hand; they won't need to wait years until their textbooks are updated.

As detailed in Table 1, the cost of developing and maintaining 6 CITEs over the 10 year period is roughly $500 million. While on the surface this figure might seem high, we hasten to point out: (1) that this amount would be spent over a 10 year period, and (2) if we can use the F-14 fighter plane as a unit of measure, the CITE portion of Option 1 can be viewed as costing less than one F-14 per year for 10 years. It is important to note that what we are proposing would not "naturally" happen: current levels of funding for research and development in education do not come close to what is needed, nor would the commercial or DOD sectors naturally put forward this level of support. Thus a major "delta" is needed by the Federal government in order to make this plan happen.

Support for Individual Investigators and Commercial Concerns

While Centers for Interactive Technologies in Education will be the major cost of Phase 1, there is a second mechanism that needs to be in place to insure progress in this area. Namely, support will still be needed for individual investigators working at their home institutions. Centers by their nature will encourage a focusing of attention on specific problems from specific paradigms. However, the independence of the individual investigator allows him/her to be less tied to a reigning paradigm. Note too that graduate students are often supported by such research grants. Moreover, given the variety of directions within education science and technology, we need many projects that explore the myriad of potential avenues. While current funding levels appear to be only marginally adequate for even today's researchers, as the field grows more and more individuals will be competing for funds. Thus, this pot needs a significant infusion of funds in order to keep abreast with the increasing numbers of researchers competing for support.

In addition, we need to set up a mechanism by which developers of technology-based products can gain support for their efforts. For example, currently software houses are frankly loathe to undertake development for the education market: development costs are high, and the market is perceived as limited and fickle. Upfront risk money and planned subcontracts through CITEs could be provided to ease the burden of developers; a return of the percentage of profits would be an acceptable cost for this type of assistance.

Phase 2: Begin Dissemination of Ideas and Technology. The objective of Phase 2 is to begin to get the ideas and technology developed by the CITEs (and by individual investigators) out into the schools. We see two major mechanisms for this transition: (1) the active participation of the commercial sector, and (2) the use of technology itself --- high-bandwidth, nationwide computer networks, and machine readable information bases --- to provide for the dissemination of product and information. We propose that Phase 2 begin in Year 2 of Phase 1. There is no reason to wait for the completion of Phase 1: the development of both mechanisms will take time, and thus they should be started early, and products should already be coming out of the pipelines at the CITEs by the end of year 2 of Phase 1. Since the technological developments of this phase will interact with the commercial sector's activities, we will address this issue first.

Computer networks promise to fundamentally change how information is distributed. Right now, there are elaborate schemes for moving physical objects --- that contain graphics, text, music, etc --- from one place to another. However, it doesn't take a crystal ball to see that, if the information in those physical objects is placed on a "machine readable medium" (e.g, CD-ROM), and if each school desk is wired to a computer network which enables the student at the desk to tie into a computer thousands of miles away --- instantly ---- then access to information no longer is a problem. Any (and each) student can have all the letters written by George Washington to Benjamin Franklin "on his desk" --- in micro-seconds.

We need to set in motion a systematic plan for creating just such computer networks and machine-readable databases. The DOD will continue to upgrade their telecommunications network (the ARPAnet). Education needs its champion to put up the resources for building the analogue of the national highway system for the nation's schools. Commercial concerns will contribute to this effort, since, as we argue below, it is in their best interest to have high-bandwidth conduits to and from schools. Similarly, while the Library of Congress will no doubt be converting portions of its collection to machine-readable form, this process also needs an extra jolt of support, focusing on high-use educational materials, in order to accelerate the process.

The agreements between CITEs and commercial enterprises ("book" publishers, software development houses, etc.) will be especially economically viable if CITEs can readily transmit products to these enterprises in a format that requires little subsequent transformation on the part of the enterprises themselves. For example, if a CITE personnel wants to publish a book, the cost of producing a hardcopy version of that book would certainly be reduced if the author can simply transmit machine-readable text directly to the typesetters. Similarly, if "book" publishers can transmit to customers essentially what the author sends in, then the cost will again be reduced. The mechanism for both transmissions is computer networks. Clearly issues of copyright, cost, etc. need to be thought through and equitably worked out (e.g., a charge for use scheme may well be viable). Note that publishers and software houses need not wait for the existence of the computer networks to begin the process of finalizing, marketing and distributing products developed at a CITE.

State and local institutions need to enter the picture in Year 2, at the beginning of Phase 2. Clearly, they will play a key role in (1) shaping the particular products coming out of the centers, as well as (2) in planning and facilitating the dissemination paths from the CITEs to the schools. Some formula will need to be developed whereby state and local governments contribute funds to support these activities.

In effect, Phase 2 simply takes the "integration of theory with practice" one step further: ideas and products need to move from the schools associated with the CITEs to schools nationwide.

Phase 3: Accelerate to Nationwide Dissemination of Ideas and Products. During this final phase of the ramp-up effort, the objective is to make the fruits of the research and development available on a national scale. The key factors during this phase are: (1) teacher education, and (2) commercial involvement.

Not unreasonably, teachers will not have had much exposure to the ideas of education science, as we have described them here, nor to the diverse types of interactive, multi-media technology, and the educational products that employ those technologies, that are coming to be available. A significant effort needs to be made to provide teachers with professional development opportunities that will aid them in understanding and using these ideas and technology products. Summer workshops, in-service seminars, sabbatical leaves to work at a CITE, etc. will need to be supported. We can't stress this need too highly: considerable funds need to be made available for this effort.

Similarly, the ideas and technologies developed through Option 1 support need to move into schools of education, and traditional academic departments at universities and colleges. We propose that CITE staff rotate out into the academic community in order to carry the ideas and technology first hand. Similarly, we see visiting faculty playing a critically important role in facilitating the transition to non-CITE locations.

Just as teachers are the ultimate implementors, commercial concerns are the ultimate distributors. We have argued previously that incentives, supports, grants, etc. need to be developed in order to provide commercial concerns with that critically important assistance in the volatile educational market.

A National Advisory Board should be set up to oversee and assess the progress made at the various CITEs and by the other participants (individual researchers, commercial concerns). This body would not have a regulatory role. Rather, there is great need in this sort of endeavor for providing alternative perspectives: we all need help seeing the forest for the trees. The Advisory Board will provide valuable feedback to CITEs, to funding agencies, etc. on these institutions' directions and themes.

Option 1 will work only if its funding is continuous. The experts we interviewed repeatedly stressed that the infrastructure of the education science and technology field must be stable in order to attract and keep the key players, and it must be stable in order to provide for orderly transition of graduate students into career paths. While particular CITEs (or individual investigators, commercial concerns, etc.) may go "out of business" the overall level of support for the plan must be stable. While we recognize that minor glitches may arise, significant reduction in funding would be disastrous. During the last decade, support for research in science education virtually disappeared for a few years. Not unreasonably, many of the best people left the field. It is the consensus of the field that we are only now beginning to recover from that instability of funding.

Note that the CITEs will continue to operate at full capacity during Phases 2 and 3. It is not the case that they will solve the problems of education during Phase 1. Education is a dynamic process, and we need to respond to changes in principled ways. Ongoing efforts at the various CITEs (and continued support for individual investigators) will provide American education with the capacity to be both reactive and proactive to our constantly changing world.

Lest this point has gotten lost in the detail: Option 1 is one that was developed on the basis of analyzing comparable work models in other fields, and on the basis of recommendations from a broad range of leading experts in education science and technology. While there will surely be disagreement about particular points of Option 1 from our experts, we feel confident that we have represented their expert opinion fairly.

Finally, what kinds of outcomes can we predict will flow from Option 1? There are essentially two: (1) the field of education science coming into its own as a significant field of study, with rich, powerful theories that deal with real learning and teaching phenomena, and (2) a wide range of principled, technological products that should provide the critically important leverage that is needed to enable American education to meet the the challenges of the 21st century.

4.2. Option 2: Modest Increase in Federal Spending

While Option 1 called for a 10-year effort, with six Centers for Technology and Education (CITE), plus substantial increase in funding for individual investigators, Option 2 calls for the following: (1) 1-2 CITEs, plus (2) only an increment increase in support of individual investigator research. This level of funding is still substantial by comparison to the current situation. Since the community is currently productive even with limited resources, we see the increment in funding, while modest, will nonetheless result in enhanced productivity. In particular, this increased level of support should definitely result in many more spotlighted projects.

However, the main weakness of this level of support lies precisely in its producing spotlights, and not a coherent, systematic exploration of ideas and technology. The experts we interviewed by and large stated that what is needed are major demonstration projects of significant scope and duration; piecemeal demonstrations --- spotlights --- are where we are now. One or two CITEs would not be able to undertake many large-scale projects. Moreover, our experts often voiced a concern that support for only a very limited number of such large-scale projects might well be risky: only a limited number of ideas would be explorable, thereby potentially directing the field (and considerable resources) down less productive paths.

Each CITE in this option would still be a robust center: the staffing levels would be at least as high as a CITE proposed in Option 1. In fact, a CITE in this option might well have additional staffing needs. The increase is due to the enhanced role that a CITE would need to play on the national level. Essentially, a CITE would need more resources to engage in dissemination and training.

Option 2 can be viewed as the "go slow" strategy. For example, experts voiced some concern that a significant input of resources, as in Option 1, to education science at this time would raise expectations too high. Delivery on those expectations might not be forthcoming in the short term, and thus a backlash might well result. In turn, funding might be cut off precipitously. Such a boom and bust funding cycle is, as experience has taught us, particularly detrimental to a growing field.

Ultimately, the question that must be answered is this: is Option 2 commensurate with the problem? Will this level of funding make a dent in the serious problems facing American education today -- and tomorrow? While Option 2 will most definitely facilitate a growth in education science, that level of development may well be outpaced by the ever changing nature of society and the educational problems that such change engenders.

4.3. Option 3: No Increase in Federal Spending

In effect, this option is saying that the current efforts by the Federal government are sufficient to deal with the problems of education. The mechanisms currently in place will provide the ideas and products that will help America cope with its education problem. While the education science community has clearly made progress under the current mechanisms and funding arrangements, the rate of progress does not approach that of the present and arising problems in American education.

Interestingly, the commercial sector is showing increased interest in using education science ideas and technology in developing more effective training programs. Such programs, while costly, may well give companies the competitive edge that is needed. However, the focus will be clearly on training that is relevant to the concerns of the commercial enterprise. Moreover, the concepts and techniques developed in the commercial sector will, not unreasonably, be proprietary; these ideas and technological innovations will not be made widely available. In effect, the gap between learning in the workplace and learning in the school will continue to grow --- adding yet more tear to the fabric of our society.

Moreover, as the commercial sector does become more active in this area, invariably there will be a drain of skilled personnel from the educational sector into the commercial sector. With limited numbers of key investigators in the field currently, this would only exacerbate the problem.

Possibly the greatest impact of this option will be felt on the classroom teachers themselves: we have ineffective mechanisms currently for involving teachers in development, exploration, and effective use of new ideas and technology. The CITE model, with 30% of its resources going directly for "in practice" efforts, quite clearly is a mechanism that attempts to remedy a current weakness. Option 3 provides precious few options for teachers.

We desperately need new mechanisms for the production and distribution of effective educationally-oriented technological products. Our current ones simply do not encourage individuals to engage in the resource intense process needed to develop effective technological products. Again, Option 3 does not address this critical need.

In sum, we do not feel that Option 3 is a viable one --- if America is serious about its commitment to making positive changes in education.

5. References

1. Ambron, S., & Hooper, K. (1987). *Multimedia in education*. Cupertino, CA: Apple Computer, Inc:

1a. American Association for the Advancement of Science (1984). *Equity and Excellence: Compatible Goals: An Assessment of Programs that Facilitate increased access and Achievement of Females and Minorities in K-12 Mathematics and Science Education*. AAAS publication 84-14. Office of Opportunities and science. Washington, DC.: American Association for the Advancement of Science.

2. Anderson, J.R. (1982). Acquisition of cognitive skill. *Psychological Review*, *89*, 396-406.

3. Anderson, J. R. (1985). *Cognitive psychology and its implications*. (2nd ed.). San Francisco: W.H. Freeman.

4. Anderson, J.R., Boyle, C.F., & Reiser, B.J. (1985). Intelligent tutoring systems. *Science*, *228*, 456-467.

4a. Anderson, J. R., & Reiser, B. J. (1985). The LISP tutor. *Byte*, *10*, 159-178.

5. Anderson, K. T., & Beeman, W. O. (1986). *An annotated bibliography of research on computers and society*. Providence, RI: Office of Program Analysis, Institute for Research in Information and Scholarship, Brown University.

6. Anderson, R.C., Osborn, J., Tierney, R. (Eds.) (1983). *Learning to read in american schools*. Hillsdale, NJ: Erlbaum.

6a. Anderson, T. (1987). Beyond Einstein: A case study in interactive television. In S. Ambron & K. Hooper (Eds.), *Multimedia in Education* (pp. 209-233). Cupertino, CA: Apple Computer Inc.

7. Ausubel, D.P. (1968). *Educational psychology: a cognitive view*. New York: Holt, Rinehart and Winston.

8. Bairstow, J. (1986, October). CD-ROM: Mass storage for the mass market. High Technology, 44-51, 69.

9. Balkovich, E., Lerman, S., & Parmelee, R. P. (1985, November). Computing in higher education: The Athena experience. Communications of the ACM, 28, 1214-1224.

10. Beck, I.L., & Carpenter, P.A. (1986). Cognitive approaches to understanding reading. American Psychologist, 41, 1098-1105.

11. Becker, H. J. (1987, June). Instructional uses of school computers: reports from the 1985 National Survey. Issue No. 4. Center for Social Organization of Schools. Baltimore, MD: John Hopkins University.

12. Bereiter, C., & Scardamalia, M. (1986). The psychology of written composition. Hillsdale, NJ: Erlbaum.

12a. Berliner, D. (1987). In search of the expert pedagogue. Educational Researcher.

12b. Bloom, B. S. (1984). The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. Educational Researcher, June/July 1984, 4-16.

13. Bloomberg, D. (Ed.). (1986, May). Digests of Recent Research: Intelligent Systems Laboratory: Mid 1983-Mid 1986. Palo Alto, CA:XEROX Palo Alto Research Centers.

13a. Bobrow, D. G. (1975). Dimensions of representation. In D. G. Bobrow & A. Collins (Ed.), Representation and understanding: Studies in cognitive science (pp. 1-34). New York: Academic Press.

14. Bobrow, D. G. (1985). (Ed.). Qualitative reasoning about physical systems. Cambridge, MA: MIT Press.

14a. Bonar, J., & Soloway, E. (1985). Preprogramming knowledge: A major source of misconceptions in novice programmers. Human-Computer Interaction, 1, 133-161.

15. Boorstin, D.J. (1980). *Greshman's Law: Knowledge or information?* Washington, DC: Library of Congress.

16. Bork, A., & Weinstock, H. (1987). *Designing computer-based learning material*. New York: Springer-Verlag.

17. Boyer, E.L. (1983). *High School: A Report on Secondary Education in America*. New York: Harper and Row.

18. Bransford, J., Hasselbring, T., Barron, B., Kulewicz, S., Littlefield, J., & Goin, L. (1987). Uses of macro-contexts to facilitate mathematical thinking. In R. Charles & E. Silver (Eds.), *Teaching and evaluating mathematical problem solving*. Reston VA: National Council of Teachers of Mathematics, in press.

19. Bransford, J., & Hasselbring, T. (1987, June). *Technology can help children who are at risk of school failure*. Paper presented at The Conference on Technology and Students at Risk of School Failure, St. Charles, Illinois, June 28-30, 1987.

20. Bransford, J., Sherwood, R., & Hasselbring, T. (1987). Effects of the video revolution on development: Some initial thoughts. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age*. Hillsdale, NJ: Erlbaum, in press.

21. Briars, D.J., & Larkin, J.H. (1984). An integrated model of skill in solving elementary word problems. *Cognition and Instruction*, *1*, 245-296.

22. Brophy, J.E. & Good, T.L. (1986). Teacher behavior and student achievement. In M.C. Wittrock (Ed.), *Handbook of Research on Teaching*, (3rd Ed.). New York: Macmillan.

23. Brown, A.L., Bransford, J.D., Ferrara, R.A., & Campione, J.C. (1983). Learning, remembering, and understanding. In J.H.Flavell & E.M. Markman (Eds.) *Handbook of child psychology: Vol. 3 Cognitive Development* (4th ed., pp. 77-166). New York, Wiley.

24. Brown, J.S. (1983). Process versus product: A perspective on tools for communal and informal electronic learning, In S. Newman and E. Poor (Eds.), *Education in the electronic age*. New York: Learning Lab, WNET/Thirteen Educational Division.

24a. Brown, J. S., Burton, R. R., & de Kleer, J. (1982). Pedagogical, natural language and knowledge engineering techniques in SOPHIE I, II, and III. In D. Sleeman & J. S. Brown (Ed.), *Intelligent tutoring systems* (pp. 227-282). New York: Academic Press.

25. Brown, J.S., & Greeno, J. (1985). (Chairmen). Research briefing panel on information technology in precollege education. In *New pathways in science and technology: Collected research briefings: 1982-1984*, (pp. 298-317). New York: Vintage Books.

25a. Brown, J. S., & VanLehn, K. (1980). Repair theory: A generative theory of bugs in procedural skills. *Cognitive Science*, *2*.

26. Bruce, B. (1986). *Information Technologies and Written Expression*. Centre for Educational Research and Innovation, Technical Report. CERI/NT/86.02. Prepared for the International Conference of National Representatives and Experts, Organization for Economic Co-operation and Development, Paris, October 13-15, 1986.

26a. Bruner, J. S. (1966). *Toward a theory of instruction*. Cambridge MA: Harvard University Press.

27. Bruno, R., & Mizushima, M. (1986, July-August). New developments in optical media: An outline of CD-I. *Optical Information Systems*, 318-323.

28. underson, C.V. (1987). *Suggested goals and priorities for federal support of research in educational technology*. Unpublished manuscript, Educational Testing Service.

29. Burton, R.R. (1982). Diagnosing bugs in a simple procedural skill. In D.Sleeman & J.S. Brown (Eds). Intelligent tutoring systems (pp.157-184). New York: Academic Press.

30. Burton, R.R., & Brown, J.S. (1982). An investigation of computer coaching for informal learning activities. In D.Sleeman & J.S. Brown (Eds.). Intelligent tutoring systems (pp. 79-98). New York: Acdemic Press.

31. Canter, M. (1986). The new workstation: CD-ROM authoring systems. In S. Lambert & S. Ropiequer (Eds.). CD Rom: The new papyrus (pp. 359-375). Redmond, WA: Microsoft Press.

32. Carey, S. (1985). Conceptual change in childhood. Boston, MA: Bradford Books/The MIT Press.

33. Carey, S. (1986). Cognitive science and science education. American Psychologist, 41, 1123-1130.

34. Carnegie Forum on Education and the Economy. (1986). A Nation Prepared: Teachers for the 21st Century. The Report of the Task Force on Teaching as a Profession. Washington, D.C.

35. Carpenter, T.P. (1985). Learning to add: An exercise in problem solving. In E. Silver (Ed.). Teaching and learning mathematical problem solving: Multiple research perspectives. Hillsdale, NJ: Lawrence Erlbaum Associates

36. Carpenter, T.P., Lindquist, M.M., Matthews, W., & Silver, E.A. (1984). Achievement in mathematics: Results from the national assessment. Elementary School Journal, 84, 485-495.

37. Carraher, T.N., Carraher, D.W., & Schliemann, A.D. (1985). Mathematics in the streets and in schools. British Journal of Development Psychology, 3, 21-29.

38. Case, R. (1985). Intellectual development: Birth to adulthood. New York: Academic Press.

38a. Chaiklin, S., & Roth, C. (Eds.) (in preparation). Physics knowledge and instruction. (Papers presented at the 1986 NSF Bank Street College Conference on Novice Physics Problem Solving and Education).

39. Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. Educational Psychologist, 17, 31-53.

40. Champagne, A.B., Klopfer, L.E., & Gunstone, R.F. (1985). Instructional consequences of students' knowledge about physical phenomena. In A.L. Pines and L.H.T. West (Eds.), Cognitive structure and conceptual change. New York: Academic Press.

41. Chi, M.T.H., Feltovich, P.J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5, 87-119.

42. Chipman, S., & Butler, P. A. (1985, July 5). Gazing into the silicon chip: The impact of microcomputers on teaching and learning. Learning Technology Center Technical Report #85.2.3, Peabody College of Vanderbilt University, Nashville TN.

43. Chipman, S.F., and Thomas, V.G. (1984). The Participation of Women and Minorities in Mathematical, Scientific, and Technical Fields. Paper prepared for the Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council, Washington, D.C.

44. Chipman, S.F., Segal, J.W., & Glaser, R. (1985). (Eds), Thinking and learning skills: Current research and open questions, (Vol. 2). Hillsdale, NJ: Erlbaum.

45. Chubin, D.E. (1986). Interdisciplinary integration within technology assessments. In Daryl E. Chubin, Alan L. Porter, Frederick A. Rossini, and Terry Connelly, eds., Interdisciplinary Analysis and Research:and Terry Connelly (Eds.), Interdisciplinary Analysis and Research: Theory and Practice of Problem-Focused Research and Development: Selected Readings. Mt. Airy, MD: Lomond Publications, Inc.

46. Clancey, W.J. (1983). The epistemology of a rule-based expert system: A framework for explanation. Artificial Intelligence, 20, 215-252.

47. Clancey, W.J. (in press). Qualitative student models. Annual Review of Computer Science. Palo Alto: Annual Reviews, Inc.

48. Clement, J. (1982). Students' preconceptions in introductory mechanics. American Journal of Physics, 50, 66-71.

49. Cole, J.Y. (1987). (Ed.). Books in our future: Perspectives and proposals. Washington, DC: Library of Congress.

50. Cole, M., and Griffin, P. (1987). Contextual Factors in Education: Improving Science and Mathematics Education for Minorities and Women. Prepared for the Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council. Madison, WI.: Wisconsin Center for Education Research.

51. Collins, A. M., & Brown, J.S. (in press, a). The computer as a tool for learning through reflection. In H. Mandl & A. Lesgold (Eds.), Learning issues for intelligent tutoring systems. New York: Springer.

52. Collins, A.M., & Brown, J.S. (in press, b). The new apprenticeship: Teaching students the craft of reading, writing, and mathematics. In L.B. Resnick (Ed.), Cognition and instruction: Issues and agendas. Hillsdale, NJ: Erlbaum.

53. Collins, A.M. (1985). Teaching, reading, and writing with personal computers. In J. Orasanu, (Ed.), A Decade of Reading Research: Implications for Practice. Hillsdale, NJ.: Erlbaum.

54. Committee on Basic Research in the Behavioral and Social Sciences. (1987). Ten-Year Outlook on Research Opportunities in the Behavioral and Social Sciences. Final report of the committee, Commission on Behavioral and Social Sciences and Education. Washington, D.C.: National Academy Press.

55. Conference Board of the Mathematical Sciences (1983). The mathematical sciences curriculum K-12: What is still fundamental and what is not. In The National Science Board Commission on Precollege Education in Mathematics, Science and Technology, Educating Americans for the 21st Century (Source Materials: pp. 1-23). Washington DC: National Science Foundation.

56. Conklin, J. (1987). A survey of hypertext. IEEE Computer, in press.

57. Crosswhite, F.J., Dossey, J.A., Swafford, J.O., McKnight, C.C., & Cooney, T.J. (1985). Second International Mathematics Study Summary Report for the United States. Champaign, Ill.: Stripes Publishing Company.

58. Driver, R., Guesne, E., & Tiberghien, A. (1985). (Eds.). Children's ideas in science. Philadelphia: Open University Press.

58a. de Beaugrande, R. (1984). Text production: Toward a science of composition. Norwood, NJ: Ablex.

59. deKleer, J. (1985). How circuits work. In D.G. Bobrow (Ed.). Qualitative reasoning about physical systems. Cambridge, MA: MIT Press.

60. diSessa, A. A.(1982). Unlearning Aristotelian physics: A study of knowledge-based learning. Cognitive Science, 6, 37-75.

61. diSessa, A.A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds.). Mental models (pp. 15-33). Hillsdale, NJ: Erlbaum.

62. diSessa, A.A. (1984, September). The Third Revolution in Computers and Education. Prepared for the Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council.

62a. diSessa, A. A. (1985). Knowledge in pieces. Address presented to the Piaget Society Symposium on "Constructivism in the Computer Age," Philadelphia, PA.

63. diSessa, A. A. & Abelson, H. (1986). BOXER: A reconstructable computational medium. Communications of the ACM, 29(9), 859-868.

63a. Dweck, C. (1986). Motivational processes affecting learning. American Psychologist, 41, 1040-1048.

64. Education Commission of the States (1983). A 50-State Survey of initiatives in science, mathematics and computer education. No. sm-83-1. Denver, CO: Education Commission of the states.

65. Education Turnkey Systems, Inc. (1985). Uses of Computers in Education. Washington, DC.: National Commission for Employment Policy.

65a. Educational Technology Center (1987). Teaching for understanding in the age of technology: A position paper from the Educational Technology Center, Harvard Graduate School of Education. Cambridge, MA: Harvard University.

66. Estes, W.K., Shiffrin, R.M., Simon, H.A., and Smith, E.E. (1982). The science of cognition. In National Research Council, Outlook for Science and Technology: The next Five Years. San Francisco: W.H. Freeman.

67. Feuerstein, R., Rand, Y., Hoffman, M.B., & Miller, R. (1980). Instrumental enrichment. Baltimore, MD: University Park Press.

68. Fey, J.T. (1982). Mathematics education. In H.E.Mitzel (Ed.), Encyclopedia of educational research. (5th ed.), Vol. 3, pp. 1166-1182. New York: Free Press.

68a. Fleming, M. L. (1979). On pictures in educational research. Instructional Science, 8, 235-251.

69. Forbus, K.D. (1985). Qualitative process theory. In D.G. Bobrow (Ed.), Qualitative Reasoning about Physical Systems. Cambridge, MA: MIT Press.

70. Frase, L. T. (1987). Technology, reading, and writing. In J. R. Squire (Ed.), The dynamics of language learning (pp. 294-308). Urbana IL: National Conference on Research in English, ERIC Clearinghouse on Reading and Communication Skills.

70a. Frederiksen, J. R., Warren, B. M., & Rosebery, A. S. (1985a). A componential approach to training reading skills: Part 1. Perceptual units training. Cognition and Instruction, 2, 91-130.

70b. Frederiksen, J. R., Warren, B. M., & Rosebery, A. S. (1985b). A componential approach to training reading skills: Part 2. Decoding and use of context. Cognition and Instruction, 3/4, 271-338.

71. Frederiksen, N. (1984). The real test bias: influences of testing on teaching and learning. American Psychologist, 39(3), 193-202.

71a. Frye, D., Soloway, E. (1987) Interfaces to educational software: A neglected topic, Proceedings of the Computer-Human Interaction Conference '87, Toronto, Canada.

72. Gagne, R.M. (1985). The conditions of learning and the theory of instruction (4th ed.). New York: Holt, Rinehart & Winston.

73. Gardner, H. (1985). The Mind's New Science: a History of the Cognitive Revolution. New York: Basic Books, Inc.

74. Gelman, R., & Brown, A.L. (1986). Changing views of cognitive competence in the young. In N.J. Smelser & D.R. Gerstein (Eds.), Behavioral and social science: Fifty years of discovery (pp. 175-207). Washington, DC: National Academy Press.

75. Gelman, R., & Gallistel, C.R. (1978). The child's understanding of number. Cambridge, MA: Harvard University Press.

75a. Gick, M. L., & Holyoak, K. J. (in press). The cognitive basis of knowledge transfer. In S. M. Cormier & J. D. Hagman (Eds.), Transfer of learning: Contemporary research and applications. Orlando, FL: Academic Press.

76. Glaser, R. (1984). Education and thinking: the role of knowledge. American Psychologist, 39(2), 93-104.

77. Glaser, R. (1987). The nation's report card: Improving the assessment of student achievement. Cambridge, MA: National Academy of Education, Harvard Graduate School of Education, 1987.

78. Good, T.L., Marshall, S. (1984). Do students learn more in heterogeneous or homogeneous groups? In P.L. Peterson, L.C. Wilkinson, and M. Hallinan (Eds.), The Social Context of Instruction (pp. 15-38). London: Academic Press.

79. Goodlad, John I. (1984). A Place Called School. New York: McGraw-Hill.

80. Greeno, J. G. (1980). Psychology of learning, 1960-1980: One participant's observations. American Psychologist, 35(8), 713-728.

81. Greeno, J.G. (1983). Research on cognition and behavior relevant to education in mathematics, science, and technology. In Educating Americans for the 21st Century, Volume 2. Washington: The National Science Board Commission on Precollege Education in Mathematics, Science, and Technology.

82. Greeno, J. (1985, April). Advancing cognitive science through development of advanced instructional systems. Paper presented at the American Educational Research Association Meetings, Chicago, Illinois.

83. Greeno, J.G., Brown, J.S., Foss, C., Shalin, V., Bee, N. V., Lewis, M. W., & Vitolo, T. M. (1987, in press). Cognitive principles of problem solving and instruction. Machine Mediated Learning.

84. Greeno, J. G., & Simon, H. A. (1986). Problem solving and reasoning. In R. C. Atkinson, R. Herrnstein, G. Lindzey, and R. D. Luce (Eds.), Stevens' handbook of experimental psychology (revised ed.). New York: John Wiley & Sons.

85. Halacz, F.G., Moran, T.P., & Trigg, R.H. (1987, April). Notecards in a nutshell. Proceedings of the ACM CHI & GI '87 Conference, Toronto, Canada.

86. Hamburg, D.A. (1984, June). Science and technology in a world transformed. Science, 943-946.

86a. Halff, H. M., Hollan, J. D., & Hutchins, E. L. (1986). Cognitive science and military training. American Psychologist, 41, 1131-1139.

87. Handscombe, R.D. (1983). University-based technology transfer. In S.R. Epton, R.L. Payne, and A.W. Pearson, (Eds.), Managing Interdisciplinary Research. Chichester, Great Britain: John Wiley & Sons.

88. Harms, N.C., Yager, R.E., (Eds.) (1981). What Research Says to the Science Teacher. Washington, DC: National Science Teachers Association.

89. Hawkins, J., & Pea, R.D. (1987). Tools for bridging the cultures of everyday and scientific thinking. Journal for Research in Science Teaching, 24, 291-307.

89a. Hegarty, M., & Just, M. A. (in press). Understanding machines from text and diagrams. In H. Mandl & J. R. Levin (Eds.), Knowledge acquisition from text and pictures. Elsevier Science Publisher B.V.: North Holland.

90. Hiltz, S.R. & Turoff, M. (1985). Structuring computer-mediated communication systems to aviod information overload. Communications of the ACM, 28,680-689.

91. Hirsch, E.D., Jr. (1987). Cultural literacy. New York: Houghton-Miffin.

92. Holdzom, D., Lutz, P.B. (1984). Research Within Reach: Science Education. Washington DC.: National Institute of Education.

93. Holmes Group (1986). Tomorrow's Teachers. East Lansing, Mich.: Michigan State University.

93a. Hooper, K. (1979). Intelligent pictures. Paper presented at the Wellesley College, Luce Foundation Series on Language and Cognition.

94. Hutchins, E., Hollan, E., & Norman, D.A. (1986). Direct manipulation interfaces. In D.A. Norman & S. Draper (Eds.), User-centered system design. Hillsdale, NJ: Erlbaum.

95. Institute for Research on Learning. (1987, March). A view of the Institute for Research on Learning. Palo Alto, CA.

95a. Jackson, P. (1986). Introduction to expert systems. Reading, MA: Addison-Wesley.

95b. Johnson, W. L., Soloway, E. (1985) Automatic Bug Detection. Byte Magazine, April.

96. Just, M. (1987). Psychology of reading and language comprehension. Boston: Allyn & Bacon.

97. Kaput, J., Luke, C., Poholsky, J., & Sayer, A. (1986, September). The role of representations in reasoning with intensive quantities. Technical Report 86-9, Harvard University, Educational Technology Center.

98. Kay, A.C. (1983). New directions for novice programming in the 1980's. In P.J.L. Wallis (Ed.), Programming technology (Vol. 2, pp. 209-247). Elmsford, NY: Pergammon Infotech.

99. Kiesler, S.B., Turner, C.F., (Eds.) (1977). Fundamental Research and the Process of Education. Committee on Fundamental Research Relevant to Education, National Research Council. Washington, DC.: National Academy of Sciences.

99a. Kiesler, S.B., Sproull, L. (1987) The computer and change on the campus, Cambridge: Cambridge University Press.

100. Kintsch, W., & Greeno, J.G. (1985). Understanding and solving word arithmetic problems. Psychological Review, 92, 109-129.

100a. Kirsch, I., & Jungeblut, A. (1986). Literacy: Profiles of America's Young Adults: Final Report. Report No. 16-PL-02. Princeton NJ: Educational Testing Service.

101. Kling, R. (1987, in press). Defining the boundaries of computing across complex organizations. To appear in R. Boland and R. Hirschheim (Eds.), Critical issues and information systems research. John Wiley and Sons.

101a. Kurland, D. M., & Pea, R. D. (1985). Children's mental models of recursive Logo programs. Journal of Educational Computing Research, 1(2), 235-243.

102. Laboratory of Comparative Human Cognition. (1983). Culture and cognitive development. In W. Kessen (Ed.), Mussen's handbook of child psychology (4th ed.), (Vol. 1, pp. 295-356). New York: Wiley.

103. Laird, J. E., Newell, A., & Rosenbloom, P. S. (1987, January). Soar: An architecture for general intelligence. Cognitive Science and Machine Intelligence Laboratory, Technical Report No. 2. Ann Arbor, MI: University of Michigan. (To appear in Artificial Intelligence.)

104. Lambert, S. and Ropiequet, S. (1986). CD-ROM: The New Papyrus. Richmond, WA: Microsoft Press.

105. Landauer, T. K. (1987). Education in a world of omnipotent and omniscient technology. To appear in R. Nickerson & P. Zodhiates (Eds.), Education in 2020: Roles for technology. Hillsdale, NJ: Erlbaum.

106. Larkin, J.H. (1982). The cognition of learning physics. American Journal of Physics, 49, 534-541.

107. Larkin, J.H., McDermott, J., Simon, D.P. & Simon, H.A. (1980). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

107a. Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. Cognitive Science, 11, 65-99.

108. Lave, J. (1987). Cognition in Practice. New York: Cambridge University Press.

109. Lawler, R., & Yazdani, M. (1987). (Eds.). Artificial intelligence and education. Norwood NJ: Ablex.

109a. Leinhardt, G. (1983). Novice and expert knowledge of individual students' achievements. Educational Psychologist, 18(3), 165-179.

110. Lepper, M. R. (1985). Microcomputers in Education: Motivational and social issues, American Psychologist, 40, 1-18.

111. Lepper, M.R., Malone, T.W. (1985). Intrinsic motivation and instructional effectiveness in computer-based education. In R.E. Snow and M.C. Farr, (Eds.), Aptitude, Learning and Instruction: III. Cognitive and Affective Process Analyses. Hillsdale, NJ.: Erlbaum.

112. Lesgold, A. M. (1986). Chairman's report. Prepared for the International Conference of National Representatives and Experts, Organization for Economic Co-operation and Development, Centre for Educational Research and Innovation, Paris, October 13-15, 1986.

113. Lesgold, A.M., & Reif, F. (1983, June). Computers in education: Realizing the potential (Chairmen's report of a research conference, Pittsburgh, PA, November 20-24, 1982). Washington, DC: U.S. Department of Education Office of Educational Research and Improvement.

114. Levin, J. A., Riel, M. M., Rowe, R. D., & Boruta, M. J. (1985). Muktuk meets jacuzzi: Computer networks and elementary school writers. In S. W. Freedman (Ed.), The acquisition of written language: Revision and response. Hillsdale, NJ: Erlbaum.

115. Lightfoot, S.L. (1983). The Good High School. New York: Basic Books.

116. Linn, M. (1986, August). Teaching in the information age--Education and the challenge of technology: Proceedings of a Conference on Technology and Teacher Education, August 5-8, 1986, Monterey, California. Cupertino, CA: Apple Computer, Inc.

116a. Linn, M. C. (1986, May). Establishing a research base for science education: Challenges, trends, and recommendations (Report of a national conference, funded by the National Science Foundation, held January 16-19, 1986). Lawrence Hall of Science and the Graduate School of Education, University of California, Berkeley.

117. Lippman, A. (1981). Movie manuals: Personalized cinema as an instructional partner. Media Technology Group, Massachusetts Institute of Technology.

117a. Littman, D., Pinto, J., Soloway, E. (1986) An analysis of tutorial reasoning about programming bugs, Proceedings of National Conference on Artificial Intelligence, Philadelphia.

117b. Littman, D., Soloway, E., (1987) Evaluating intelligent tutoring systems: The cognitive science perspective, in J. Jeff Richardson, M. Polson (Eds.), Intelligent Tutoring Systems, Hillsdale, NJ: Erlbaum.

117b. Littman, D., Pinto, J., Soloway, E. (1986) An analysis of tutorial reasoning about programming bugs, Proceedings of National Conference on Artificial Intelligence. Philadelphia.

118. Learning Research and Development Center (1987, May). Research in intelligent CAI at the Learning Research and Development Center of the University of Pittsburgh. Pittsburgh PA.

119. Malone, T.W., Grant, K.R., Turbak, F.A., Brobst, S.A., & Cohen, M.D. (1987). Intelligent information sharing systems. Communications of the ACM, in press.

119a. Mandl, H., & Levin, J. R. (in press). (Eds.), Knowledge acquisition from text and pictures. Elsevier Science Publisher B.V.: North Holland.

120. March, J. G. (1985). (Chair). Mathematics, science, and technology education: A research agenda. Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council. Washington DC: National Academy Press.

121. March, J. G. (1987). (Chair). Interdisciplinary research in mathematics, science, and technology education. Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council. Washington DC: National Academy Press.

122. McCloskey, M., Caramazza, A., Green B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. Science, 210,1139-1141.

122a. McConkie, G. W., Zola, D., & Winograd, P. (in press). Computer aided reading for adult illiterates. In M. Pennington (Ed.), Teaching English with computers: First and second language perspectives.

123. McDermott, L.C. (1984). Research on conceptual understanding in mechanics. Physics Today, 37, 24-32.

124. Mehan, H. (1979). *Learning lessons*. Cambridge, MA: Harvard University Press.

125. Meichenbaum, D. (1977). *Cognitive behavior modification: An integrated approach*. New York: Plenum.

126. Melmed, A. (1987, May). *A new educational technology: need and opportunity*. Paper presented at Lugano, Switzerland Conference on Computer-Assisted Approaches to Training, sponsored by the Gottlieb-Duttweiler Institute, Zurich, Switzerland in collaboration with New York University. Proceedings to be published by North-Holland Press.

127. Meyers, L. F. (1984). Unique contributions of microcomputers to language intervention with handicapped children. *Seminars in Speech and Language*, *5*.

127a. Mikulecky, L. (1982). Job literacy: The relationship between school preparation and workplace actuality. *Reading Reseach Quarterly*, *17*, 400-419.

127b. Miller, G. A.,& Gildea, P. M. (1987, September). How children learn words. *Scientific American*, *257*(3), 94-99.

128. Minstrell, J. (1982). Conceptual Development Research in the Natural Setting of the Classroom. In M. B. Rowe (Ed.). *Education in the 80's --science*. Washington, DC: National Education Association.

129. Morris, J.H. et al. (1986, March). Andrew: A distributed personal computing environment. *Communications of the ACM*, *29*(3), 184-201.

129b. National Assessment of Educational Progress. (1986). *The Reading Report Card: Trends in reading over four national assessments 1971-1984*. Princeton, NJ: Educational Testing Service.

130. National Commission on Excellence in Education. (1983). *A nation at risk: The imperative for educational reform*. Washington, DC: U.S. Government Printing Office.

131. National Council of Teachers of Mathematics (1980). An agenda for action: Recommendations for school mathematics in the 1980's. Reston, VA: National Council of Teachers of Mathematics.

131a. National Science Board Commission on Precollege Education in Mathematics, Science and Technology (1983). Educating Americans for the 21st Century: A plan of action for improving mathematics, science, and technology education for all American elementary and secondary students so that their achievement is the best in the world by 1995. Washington DC: National Science Foundation.

132. Negroponte, N. (1987). MIT Media Laboratory. Annual Report of Activities (Videodisc).

133. Neisser, U. (1987). (Ed.). School achievement of minority children: New perspectives. Hillsdale, NJ: Lawrence Erlbaum Associates.

133a. Newman, D., Goldman, S., Brienne, D., & Jackson, I. (1987). Earth Lab: Progress Report, May 1, 1986 to December 31, 1986. Technical Report. Center for Children and Technology. New York: Bank Street College of Education.

134. Nickerson, R. S. (1985, Summer). Adult literacy and technology. Visible Language, 19(3), 311-355.

134a. Nickerson, R. S. (1985) Understanding understanding. American Journal of Education, vol. 93, pages 201-239.

135. Nickerson, R. S. (1986b, October). Technology in education in 2020: Thinking about the not-distant future. Background paper for Harvard Educational Technology Center Panel on Technology in Education in 2020, Vermont.

136. Nickerson, R. S. (1986c). Using computers: The human factors of information systems. Cambridge, MA: MIT Press.

137. Nickerson, R. S. (1986a, May 2). Preliminary notes re: psychological research priorities. Prepared for American Psychological Association Ad Hoc Planning Group on Scientific Developments, chaired by Lew Lipsitt.

138. Nielsen, J. (1987). Computer-supported cooperative work: Trip report from the conference in Austin, December 3-5, 1986. SIGCHI Bulletin, 19(1), 54-61.

139. Norcio, A. F., & O'Hare, J. J. (1987, April 24). (Eds.). Report on the Workshop on Research and Development in Naval Human-Computer Interactive Systems. NRL Memorandum Report 5971. Washington, DC: Naval Research Laboratory.

140. Novak, J.D., & Gowen, D.B. (1984). Learning how to learn. Cambridge: Cambridge University Press.

141. Ong, W. J. (1982). Orality and literacy: Technologizing the word. New York: Methuen.

142. Osborne, R., & Freyberg, P. (1985). Learning in science. Auckland, Australia: Heineman Publishers.

143. Palincsar, A., & Brown, A.L. (1984). Reciprocal teaching of comprehension- fostering and comprehension-monitoring activities. Cognition and Instruction, 1, 117-176.

144. Papert, S. (1980). Mindstorms: computers, children, and powerful ideas. New York: Basic Books.

144a. Park, R. (1984). Improving basic skills in the workplace. Training and Development Journal, 76-80.

144b. Paivio, A. (1971). Imagery and verbal processes. New York: Holt, Rinehart & Winston.

145. Pea, R.D. (1985). Beyond amplification: Using the computer to reorganize human mental functioning. Educational Psychologist, 20, 167-182.

146. Pea, R.D. (1987, April). Human-machine symbiosis: Cognitive and cultural implications of hypermedia. Paper presented at an international conference on Computers, Cognition, and Epistemology, University of Aarhus, Denmark (to appear).

147. Pea, R.D. (1987, in press). Socializing the knowledge transfer problem. International Journal of Educational Research.

147a. Pea, R. D., Cohen, J., Brunner, C., Mellen, N., & Webster, K. (1987). IDEA: Tools for learning systematic decision analysis. Paper presented at the Annual Meeting of the American Educational Research Association, Washington DC.

148. Pea, R.D. and Kurland, D.M. (1987). Cognitive technologies for writing. Review of Research in Education, 14.

148a. Pea, R. D., Soloway, E., & Spohrer, J. C. (1987). The buggy path to the development of programming expertise. Focus on Learning Problems in Mathematics, 9(1), 5-30.

148aa. Peterson, P. L., Wilkinson, L. C., & Hallinan, M. (1984). (Eds.). The social context of instruction. Orlando, FL: Academic Press.

148ab. Pettito, A. L. (1985). Division of labor: Procedural learning in teacher-led small groups. Cognition and Instruction, 2, 233-270.

148b. Piaget, J., & Inhelder, B. (1969). The psychology of the child. London: Routledge & Kegan Paul.

148c. Ravitch, D., & Finn, C. E., Jr. (1987). What do our 17-year-olds know? A report on the first national assessment of history and literature. New York: Harper & Row.

149. Reif, F. (1985). Acquiring an effective understanding of scientific concepts. In L.H.T. West & A.L. Pines (Eds.), Cognitive structure and conceptual change. New York: Academic Press.

150. Reif, F. (1987). Interpretation of Scientific or Mathematical Concepts: Cognitive Issues and Instructional Implications. Cognitive Science, to appear.

150a. Resnick, D.P., & Resnick, L. B. (1977). The nature of literacy: An historical exploration. Harvard Educational Review, 47(3), 370-385.

151. Resnick, L.B. (1983). Mathematics and science learning: A new conception. Science, 220, 477-478.

152. Resnick, L.B. (1984). Toward a cognitive theory of instruction. In S.G. Paris, G.M. Olson & H.W. Stevenson (Eds.), Learning and motivation in the classroom. Hillsdale, NJ: Lawrence Erlbaum Associates.

153. Resnick, L.B. (1987). Education and Learning to Think: Subcommittee Report. Paper prepared for the Committee on Research in Mathematics, Science, and Technology Education, Commission on Behavioral and Social Sciences and Education, National Research Council, Washington, D.C.

154. Resnick, L.B. (in press). Understanding algebra. In J. Sloboda & D. Rogers (Eds.). Cognitive processes in mathematics. University of Keele, England: Oxford University Press.

154a. Resnick, L. B., & Johnson, A. (1987, July). Intelligent machines for intelligent people: Cognitive theory and the future of computer assisted learning. Unpublished manuscript. Learning Research and Development Center, University of Pittsburgh.

155. Resnick, L.B., & Omanson, S.F. (1987). Learning to understanding arithmetic. In R. Glaser (Ed.), Advances in instructional psychology (Vol. 3, pp. 41-95). Hillsdale, NJ. Erlbaum.

156. Rogoff, B., & Lave, J. (Eds.). (1984). Everyday Cognition: Its development in social context. Cambridge, MA: Harvard University Press.

157. Romberg, T.A. & Carpenter, T.P. (1985). Research on teaching and learning mathematics: Two disciplines of scientific inquiry. In M.C. Wittrock(Ed.), Handbook of research on teaching (3rd Ed.). New York: Macmillan.

158. Rosebery, A. S. (1986). (Ed.). Research digest: Cognitive and instructional sciences. Cambridge, MA: Bolt Beranek and Newman Laboratories.

159. Rosegrant, T. J. (1984). Fostering progress in literacy development: Technology and social interaction. Seminars in Speech and Language, 5, 47-57.

159a. Rothkopf, E. Z. (1987, July). Putting educational technology to work: Solutions for unglamorous problems. Unpublished manuscript. New York: Teachers College, Columbia University.

160. Rothman, R. (1987, August 7). "Summit meeting" of Leading English teachers calls for reforms in instruction at all levels. Education Week, 6(39), Extra Edition, 1, 29.

161. Rowe, M.B. (1983). Science education: A framework for decision-makers. Journal of the American Academy of Arts and Sciences, 112.

162. Rubin, A.D. and Bruce, B.C. (1986). Learning with Quill: Lessons for students, teachers and software designers. In T.E. Raphael (Ed.). Contexts of school basic literacy (pp. 217-230). NY: Random House.

163. Rumelhart, D.E., & Norman, D.A. (1981). Analogical processes in learning. In J.R. Anderson (Ed.), Cognitive skills and their acquisition. Hillsdale, NJ: Erlbaum.

164. Russell, S. J. (1987, Winter). Math in the real world: Used Numbers project explores practical skills. Hands On!, 10(1), 8, 21.

164a. Sack, W., Littman, D., Spohrer, J., Soloway, E. (1986) Evaluting the performance of PROUST in the classroom. Yale University, Department of Computer Science, Technical Report. New Haven, CT.

165. Schank, R.C. (1986). Explanation patterns: Understanding mechanically and creatively. Hillsdale, NJ: Erlbaum.

166. Schank, R. C., & Slade, S. (1985, October). Education and computers: An AI perspective. Yale University, Department of Computer Science, YALEU/CSD/RR #431. New Haven, CT.

167. Schatz, B.R. (1986, September). Telesophy: A system for browsing and sharing inside a large information space. TM-ARH-006-094. Morristown, NJ: Bell Communications Research.

167a. Schwartz, J. (1987). Dreamworlds. Daedulus.

168. Schoenfeld, A. (1985). Mathematical problem solving. New York: Academic Press.

169. Scribner, S. (1985). Knowledge at work. Anthropology and Education Quarterly, 16, 199-206.

170. Segal, J., Chipman, S., & Glaser, R. (1985). (Eds.). Thinking and learning skills: Relating instruction to basic research: Vol. 1. Hillsdale, NJ:Erlbaum

171. Sheil, B.A. (1981). Coping with Complexity. (CIS-15). Palo Alto, CA: Xerox PARC.

172. Shymansky, J.A., Kyle, W.C. Jr., Alport, J.M. (1983). The effects of new science curricula on student performance. Journal of Research in Science Teaching, 20(5), 387-404.

172a. Simon, H. A. (1981). The sciences of the artificial, 2nd ed. Cambridge MA: MIT Press.

173. Sirotnik, K.A. (1981). What You See Is What You Get: A Summary of Observations in Over 1000 Elementary and Secondary Classrooms. A Study of Schooling. Technical Report No. 29. University of California, Graduate School of Education, Laboratory in School and Community Education, Los Angeles.

174, Sizer, T. (1984). Horace's compromise: The dilemma of the American high school. New York: Houghton Mifflin.

175. Sleeman, D., & Brown, J.S. (1982). (Eds.). Intelligent tutoring systems. New York: Academic Press.

176. Smith, D.C., Irby, C., Kimball, R., & Verplank, B. (1982, April). Designing the Star user interface. Byte.

176a. Snow, R. E. (1986). Individual differences and the design of educational programs. American Psychologist, 41, 1029-1039.

176b. Snow, R. E., Frederico, P., & Montague, W. E. (1980). (Eds.). Cognitive process analysis of aptitude. Hillsdale, NJ: Erlbaum.

177. Soloway, E. (1985). From problems to programs via plans: The content and structure of knowledge for introductory LISP programming. Journal of Educational Computing Research, 1, 157-172.

177a. Soloway, E. (1986). Learning to program = Learning to construct mechanisms and explanations. Communications of the ACM, 29(9), 850-858.

177b. Spohrer, J. C., & Soloway, E. (1986). Novice mistakes: Are the folk wisdoms correct? Communications of the ACM, 29(7), 624-632.

178. Stage, E., Kreinberg, N., Eccles (Parsons), J., Becker, J. (1985). Increasing the participation and achievement of girls and women in mathematics, science and engineering. In S.S. Klein (Ed.), Handbook for achieving sex equality through education. Baltimore, Md.: John Hopkins University Press.

179. Stake, R.E. & Easley, J.A., Jr. (1978). Case studies in science education. NSF Se-78-74. Available from the U.S. Government Printing Office. Washington, DC. National Science Foundation.

180. Steen, L. A. (1987). Mathematics education: A predictor of scientific competitiveness. Science, 237, 251-252, 302.

181. Stefik, M., Foster, G., Bobrow, D.G., Kahn, K.M., Lanning, S., & Suchman, L.A. (1987). Beyond the chalkboard: Using computers to support collaboration and problem solving in meetings. Communications of the ACM, 30(1).

182. Sternberg, R. S. (1983). Criteria for intellectual skills training. Educational Researcher, 12, 6-12, 26.

183. Sternberg, R. J. (1984). (Ed.). Mechanisms of cognitive development. New York: W. H. Freeman & Co.

184. Sternberg, R. S. (1984). Toward a triarchic theory of human intelligence. The Behavioral and Brain Sciences, 7, 269-315.

185. Stevens, A., and Roberts, B. (1983). Quantitative and qualitative simulation in computer-based training. Journal of Computer-Based Instruction, 10,16-19.

185a. Sticht, T. G. (1987). Functional context education: Workshop resource handbook. San Diego, CA: The Applied Behavioral and Cognitive Sciences, Inc.

185b. Sticht, T., & Mikulecky, L. (1984). Job-related skills: Cases and conclusions. Information Series No. 285. Columbus, OH: The Ohio State University, ERIC Clearinghouse on Adult, Career, and Vocational Education.

186. Talmis (1986, May). The future of computers in education: A district-level view. Talmis #1956. New York: Talmis (215 Park Avenue South, NY NY 10003).

187. Task Force for the Study of Chemistry Education in the United States (1984). Tomorrow. Washington, DC: American Chemical Society.

188, Thurow, L. C. (1987, May). A surge in inequality. Scientific American, 256(5), 30-37.

189. Tinker, R. (1987, Winter). Network science arrives: National Geographic-coordinated school experiment generates student-scientists. Hands On!, 10(1), 1, 10-11.

190. Tinker, R. (1987, Winter). Turning math curricula upside down: Applying math models in tenth grade. Hands On!, 10(1), 9.

191. Trachtman, P. (1984, February). Putting computers into the hands of children without language. Smithsonian, 42-51.

192. Trigg, R.H., & Weiser, M. (1986). TEXTNET: A network-based approach to text handling. ACM Transactions on Office Information Systems, 4(1), 1-23.

192a. VanLehn, K. (1983). On the representation of procedures in repair theory. In H. P. Ginsburg (Ed.), The development of mathematical thinking. New York: Academic Press.

193. Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. European Journal of Science Education, 1, 205-221.

193a. Voss, J. F., Greene, T. R., Post, T. A., & Penner, B. C. (1983). Problem-solving skill in the social sciences. In G. H. Bower (Ed.), The psychology of learning and motivation: Advances in research and theory. (Vol. 17, pp. 165-213). New York: Academic Press.

194. West, L. & Pines, A.L. (1985). (Eds.). Cognitive structure and conceptual change. Orlando, FL: Academic Press.

195. Weyer, S.A., & Borning, A.H. (1985). A prototype electronic encyclopedia. ACM Transactions on Office Information Systems, 3(1), 63-88.

196. White, B.Y., and Frederiksen, J.R. (1985, July). QUEST: Qualitative Understanding of Electrical System Trouble-shooting. Sigart, 93.

197. White, B. & Frederiksen, J. (1986). Progressions of qualitative models as a foundation for intelligent learning environments. Bolt Beranek and Newman Report No. 6277. Cambridge, MA. (Artificial Intelligence, to appear).

198. White, B.Y. and Horwitz, P. (1987). ThinkerTools: Enabling Children to Understand Physical Laws. In Proceedings of the Ninth Annual Conference of the Cognitive Science Society (pp. 336-347). Hillsdale, NJ: Erlbaum.

199. White, B.Y. (1984). Designing computer games to help physics students understand Newtons laws of motion. Cognition and Instruction, 1,69-108.

200. Wilson, K.S. (1987). Palenque: An interactive multimedia optical disk prototype for children. Technical Report No. 44, Center for Children and Technology. New York: Bank Street College of Education.

201. Wiser, M. & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.). Mental models. Hillsdale, NJ: Lawrence Erlbaum & Associates.

201a. Wiser, M. (1985). Designing a microcomputer-based laboratory to induce differentiation between heat and temperature in ninth graders. Technical Report 85-17. Cambridge MA: Harvard University, Educational Technology Center.

202. Yankelovich, N., Meyrowitz, N., & van Dam, A. (1985, October). Reading and writing the electronic book. IEEE Computer, 18(10), 15-30.

203. Yff, J. (1985). (Ed.). *Education in the information age: The impact on teacher education and training. International Yearbook on Teacher Education 1985*. Washington DC: International Council on Education for Teaching.

6. Appendix A: Structured Interview Guideline Distributed to Respondents

CURRENT PROSPECTS

Question 1: List significant projects and directions

What do you consider to be the most significant recent **projects** and **thematic directions** for educational technology research and development? Please explain why.

Question 2: Appraise most promising projects/directions

Pick three projects/directions (other than your own) and explain why they are the most promising. For each, in your judgement what is the likelihood of their having significant impacts at the level of classroom implementation? When and why?

(If any of these are considered highly promising but **not** likely to have such impacts, what are the **obstacles**, or **needs to be met**, which would enable such impacts?)

Question 3: Justify "best bets" options

Of the projects/directions of work just described, what are the **one or two** you consider to be "best bets" options: i.e., lowest cost, maximum effects? Why?

Question 4: Explain "unpromising" options

Of educational technology research and development underway/supported, what are the most obvious **unpromising** projects/directions? Why do you say so?

CHALLENGES

Question 5: Define priority areas and investment strategies

What is needed **topically** for major progress or breakthroughs to occur in educational technology research and development? What important could be discovered? For each case mentioned, what **resources** are required?

Consider this question for the following levels, noting at each level the specifics that promise the greatest possible yield for education from R&D investment:

Subject areas
Projects
Programs of work
Specific technologies or products
Product paths/directions
Institutions
Specific individuals' work

Question 6: Select highest priorities

Of what you've mentioned, what do you believe to be the 3 **highest priorities** for increasing positive effects of technology on educational processes and outcomes? What do you consider to count as "positive effects"?

CRITICAL FACTORS

Question 7: Factors influencing R&D Agenda and Progress

What factors currently influence--either **positively or negatively**-- research and development agenda setting (e.g., what topics are being studied; what technologies are in use) or progress in this field? In what ways?

Some possible categories for comment, which may be added to or ignored as you consider appropriate, include:

1. Curriculum and texts
2. Equipment availability (e.g.,schools, research)
3. Funding (e.g., level, topics)
4. Institutional arrangements for R&D activities
5. Mechanisms of dissemination

6. Role of local and state governments

7. School organization (e.g., teacher education, testing, classroom practices, technology implementation and maintenance policies)

8. Staffing (e.g., adequacy of researcher, developer training; availability of scientists)

9. Technology marketplace (e.g., what's available, costs, new categories, standards)

10. Technology development trends

Question 8: Evaluation of Current Federal Role

What do you believe to be the positive and negative aspects of the **current** Federal role in advancement of significant educational technology research and development?

Question 9: Appraisal of Promising Work Models

Please offer your suggestions for several models of institutional arrangements that--if supported by the Federal government--would be likely to return high-yield impacts on educational technology research and development? What do you consider to be the **pros and cons** of each model described?

Question 10: Assessment of Unproductive Work Models

What do you consider to be the **less viable** or even **unviable** approaches to supporting educational technology research and development for significant impact on education? Why?

7. Appendix B: Major Institutions and Laboratories

Apple Computer
Bank Street College (Center for Children & Technology, Media Group)
Bell Communications Research
Berkeley (University of California)
Bolt Beranek and Newman
Brown University
Carnegie-Mellon University (Psychology, Computer Science)
Harvard University, Educational Technology Center
New York University
MCC (Microelectronics and Computer Consortium)
MIT, Media Laboratory
Princeton University
Stanford University
Technical Education Resource Centers & Lesley College
University of Illinois
University of Pittsburgh, LRDC
Vanderbilt University
Xerox PARC (Palo Alto Research Center)
Yale University

8. Appendix C: Examples of Education Science and Technology Projects

Preface. In the following descriptions, we outline prominent examples that represent the broad range of contributions to innovative applications of technology to problems at the heart of the cognitive, social, and instructional sciences of education. These representatives illustrate attention to key findings from education science, as described in Part I of our report, and the imaginative use of new technologies, for a broad range of ages and subject disciplines. Of course there are other projects of noteworthy nature, since this is by no means an exhaustive list.

Algebra Workbench
Topic: algebraic word problem-solving
Director(s): Roberts and Feurzeig
Institution: Lesley College and Bolt Beranek & Newman
Funding Source(s): NSF
Age level: 6th grade
Brief:

Extends LOGO programming application to early algebra instruction

Boxer
Topic: programming environments for nonprofessionals
Director(s): diSessa
Institution: U. California, Berkeley (formerly MIT)
Funding Source(s): NSF
Age level: Middle school to adult
Brief:

Boxer makes extensive use of graphics, well-designed interface principles, and familiar spatial metaphors to enable nonprofessionals to more easily create computer programs.

Chips
Topic: toolkit for creating graphics intensive programs
Director(s): Bonar
Institution: LRDC
Funding Source(s): DoD
Age level: mainly for designers of instructional software
Brief:

With the intent of making it easier to create graphics intensive programs, Chips is a toolkit that provides a user with manipulable graphical images.

CMU Tutor
Topic: programming environments for structured curriculum design
Director(s): Sherwood
Institution: Carnegie-Mellon University
Funding Source(s): NSF,
Age level: mainly for teachers, professors, instructional designers
Brief:

CMU Tutor is an authoring language created for use on advanced function workstations currently used in university-level educational computing, and being distributed to universities throughout the US. Building on MicroTutor, an authoring language for the Plato Project, CMU Tutor has extensive capabilities that handle text, graphics, and that facilitate diagnosis of student responses.

Debuggy
Topic: diagnosing sources of place-value subtraction errors
Director(s): Burton, VanLehn
Institution: Xerox PARC (earlier Bolt Beranek & Newman
Funding Source(s): DoD
Age level: Elementary school
Brief:

Debuggy uses artificial intelligence methods and a cognitive theory of knowledge representation to make and test inferences about the "buggy" (i.e., error-ridden) rules students are using to solve problems.

Earth Lab
Topic: collaborative studies on earth science
Director(s): Newman
Institution: Bank Street College
Funding Source(s): NSF
Age level: 6th grade
Brief:

Earth Lab uses local-area network technology inside schools and classrooms to facilitate scientific collaboration and carrying out of real experiments in a geography-based science curriculum.

Geometric Supposers
Topic: hypothesis-exploration in plane geometry
Director(s): Schwartz
Institution: Harvard University Educational Technology Center
Funding Source(s): OERI
Age level: Middle School
Brief:

Programs in the Geometric Supposer series allow students to use the computer as an electronic straight-edge and compass for making and testing conjectures about relations between construction components.

Geometry Tutor
Topic: creating geometry proofs
Director(s): Anderson & Boyle
Institution: Carnegie-Mellon University
Funding Source(s): NSF, DoD, Carnegie Foundation
Age level: 10th grade
Brief:

The Geometry Tutor facilitates a student's development of a geometric proof by making graphically explicit problem-solving search processes, and use of a cognitive theory-driven student modelling component provides fine-grained error diagnosis and tailored help.

Green Globs
Topic: understanding algebraic functions and graphs
Director(s): Dugdale
Institution: University of Illinois
Funding Source(s): NIE, NSF
Age level: Middleschool
Brief:

Green Globs uses motivating game techniques and linked representations (i.e., graph, algebraic equation) to foster the development of intuitive relations between changes in the form of an equation and its graphic shape.

Guidon
Topic: medical diagnostic skills
Director(s): Clancey
Institution: Stanford
Funding Source(s): DoD, Macy Foundation
Age level: Postgraduate
Brief:

Guidon is a series of artificial-intelligence based tutors for instructing physicians in disease diagnostic skills. A key component of this effort has been explicating the tacit knowledge and skills needed for this activity.

Heat and Temperature
Topic: differentiating concepts of heat and temperature
Director(s): Wiser & Carey
Institution: Harvard Educational Technology Center
Funding Source(s): NIE, OERI

Age level: 9th grade
Brief:

This project uses dynamic visual representations of heat flow in a microcomputer lab (normally unobservable) to help students learn- by-doing how to distinguish the concepts of heat and temperature, central to understanding energy transfer throughout secondary school and traditionally a major obstacle of physics education.

IDEA
Topic: systematic decision analysis
Director(s): Pea
Institution: New York University
Funding Source(s): Spencer Foundation
Age level: Middleschool to adult
Brief:

IDEA allows middleschool age students to learn how to apply systematic decision methods such as multi-attribute utility theory to school-based and everyday decision problems. The project embodies cognitive theory concerning critical conditions for learning generalizable thinking skills, and employs an active explicit map of the decision-making process as a task-navigational aid.

Inquire
Topic: systematic scientific inquiry
Director(s): Hawkins
Institution: Bank Street College
Funding Source(s): NSF
Age level: Middleschool
Brief:

The Inquire Project has created a set of tool programs that collectively encourage a structured, systematic approach to constructing conjectures about some scientific phenomenon, explicating prior knowledge and questions about it, and carrying out an inquiry process. involving both qualitative and quantitative activities. It highlights the role of the student as constructing scientific understanding, not only learning facts.

Intermedia

Topic: hypermedia information environment
Director(s): Meyrowitz & Yankelovich
Institution: Brown University
Funding Source(s): Annenberg, Apple Computer
Age level: Undergraduate
Brief:

The Intermedia Project has created an advanced function workstation hypermedia environment for "linking" together for instruction images, text, timelines, and other representations that can be browsed and commented upon in a networked classroom environment. Full courses in cell biology and 19th century English literature using Intermedia have been implemented.

Kids Network Project

Topic: collaborative science experiments using telecommunications networks
Director(s): Tinker
Institution: Technical Education Resource Centers and National Geographic
Funding Source(s): NSF, National Geographic Society
Age level: 4th-6th grade
Brief:

The Kids Network Project is a private-public partnership that is creating classroom activities for nationwide "network science" experiments in which students across the country will collaborate on real, large-scale experiments on such topics as acid rain, weather forecasting, water pollution, and food growing.

Lego-Logo

Topic: design and control of robot-like objects
Director(s): Papert
Institution: MIT
Funding Source(s): ---
Age level: Elementary
Brief:

> Lego-Logo is an interdisciplinary activity (mathematics, science, engineering) that allows elementary school children to control familiar Lego machines and blocks through Logo computer programs.

Lisp Tutor

Topic: introductory Lisp programming
Director(s): Anderson
Institution: CMU
Funding Source(s): DoD
Age level: high school and beyond
Brief:

> The Lisp Tutor, an intelligent tutoring system for the domain of introductory Lisp programming, has been running at CMU for several years on a regular basis with most satisfactory results. Based on a fine-grained, cognitive theory of skill acquisition (ACT*), the Lisp Tutor traces a student's progress and provides tailored instruction.

Logo

Topic: introductory programming
Director(s): Papert & Feurzeig
Institution: MIT & Bolt, Beranek, Newman, Inc.
Funding Source(s): DoD, NSF
Age level: elementary school and beyond
Brief:

Logo, a programming language expressly designed to teach the concepts of programming to non-professionals, is used nationwide in the schools. Its graphics orientation and minimal syntax enable it to be both motivating and accessible to students.

Macro-contexts Project
Topic: science learning in functional contexts
Director(s): Sherwood and Bransford
Institution: Vanderbilt University
Funding Source(s): IBM, DoD
Age level: Middle School
Brief:

The Macro-contexts Project uses interactive video technologies to provide captivating life contexts for seeing the point of scientific and mathematical reasoning; research suggests such techniques may have special applicability for motivating at-risk students.

Microcomputer-Based Laboratory
Topic: inquiry-oriented science tools
Director(s): Tinker
Institution: Technical Education Research Centers
Funding Source(s): NSF, DOE
Age level: Elementary school and up
Brief:

The Microcomputer-Based Laboratories created by TERC have had a large impact on science education by placing into children's hands scientists' tools such as graphing software and temperature, motion, light, and sound data-collection hardware that connects to classroom computers.

Modelling Project
Topic: systems dynamics (calculus)
Director(s): Tinker and Roberts
Institution: Technical Education Research Centers and Lesley College

Funding Source(s): NSF
Age level: 10th grade
Brief:

Computer-based tools let 10th graders do systems dynamics model building of situations such as population growth without requiring them to first understand differential equations.

Palenque
Topic: Mayan archaeology, biology, and culture
Director(s): Wilson
Institution: Bank Street College
Funding Source(s): GE/RCA
Age level: Elementary
Brief:

Palenque is an interactive prototype of informal educational technology using new digital-video interactive technology. Palenque, a Mayan archaeological site in the Yucatan, can be explored in a variety of novel, computer-assisted ways.

Proust
Topic: diagnosing non-syntactic bugs in student Pascal programs
Director(s): Johnson & Soloway
Institution: Yale University
Funding Source(s): DoD
Age level: middle school and beyond
Brief:

Proust attempts to provide students with a diagnosis of the non-syntactic bugs in their Pascal programs. While limited in scope, classroom tests of Proust have shown it to be both accurate in its diagnosis and educationally beneficial.

Quest
Topic: basic electrical theory
Director(s): White & Frederiksen
Institution: Bolt, Beranek, Newman, Inc.

Funding Source(s): DoD
Age level: high school
Brief:

- Quest is a micro-world, simulation environment for teaching qualitative reasoning about electrical circuits. Key is Quest's capacity to make available micro-worlds of increasing complexity, that in turn facilitate the transition from novice to expert.

Quill
Topic: writing skills
Director(s): Bruce & Rubin
Institution: Bolt, Beranek, Newman, Inc.
Funding Source(s): ---
Age level: elementary school
Brief:

Quill is a set of microcomputer-based writing activities that facilitates students' writing real documents, e.g., newsletters, brochures. Quill is currently being used in more than 2,000 classrooms.

Rat
Topic: rational number arithmetic
Director(s): Resnick & Ohlsson
Institution: LRDC
Funding Source(s): NSF
Age level: elementary school
Brief:

With the goal of teaching basic arithmetic concepts such as fraction, ratio, etc., a series of micro-worlds is being developed. Key in these environments is the ability for the child to interact with (and operate on) various graphical representations of everyday objects.

Reasoning under Uncertainty

Topic: introductory statistical reasoning
Director(s): Swets, Bruce & Feurzeig
Institution: Bolt Beranek & Newman
Funding Source(s): NSF
Age level: High school
Brief:

The Reasoning under Uncertainty Project is creating software tools for high school students to use to learn to reason statistically much earlier than believed possible. Their cognitive approach emphasizes reasoning processes and their relation to real-world opportunities for using statistical reasoning to understand things.

Sketch
Topic: graphing skills
Director(s): Larkin
Institution: CMU
Funding Source(s): NSF
Age level: middle school and beyond
Brief:

Sketch is a tutor designed to aid in the development of the visualization skills needed to quickly sketch graphs of simple algebraic expressions. Sketch has a built-in model for problem solving, and a coach for helping students apply the problem solving model.

Smithtown
Topic: microeconomics
Director(s): Glaser. Bonar, Raghavan, Schultz, Shute
Institution: LRDC
Funding Source(s): DoD
Age level: high school and up
Brief:

Smithtown is a discovery world for microeconomics; it is one of a series of scientific discovery worlds under development at

LRDC. Graphical simulation allows a student to carry out actions in this micro-world, observe the results, and develop more general characterizations of interactions.

Sophie
Topic: electronic troubleshooting skills
Director(s): Brown & Burton
Institution: Xerox PARC (earlier at Bolt, Beranek, Newman, Inc.)
Funding Source(s): DoD
Age level: high school and beyond
Brief:

The Sophie project produced a series of systems, in the domain of electronic troubleshooting, each of which explored different aspects of the concept of a "reactive learning environment." These systems supported the student in developing hypotheses as to the fault in the circuit, conducting tests on the circuit, and interpreting the results obtained.

Steamer
Topic: operation of a steam propulsion power plant
Director(s): Stevens
Institution: Bolt, Beranek, Newman, Inc.
Funding Source(s): DoD
Age level: vocational training
Brief:

Steamer attempted to provide trainees with a qualitative understanding of the complex inter-relationships among components in a steam propulsion plant aboard a ship. Graphical simulation was a key component of the learning environment.

ThinkerTools
Topic: introductory Newtonian mechanics
Director(s): White and Horwitz
Institution: Bolt Beranek & Newman
Funding Source(s): NSF

Age level: sixth grade
Brief:

ThinkerTools is a simulation using a video game-like format for helping 6th graders learn basic concepts in Newtonian mechanics such as mass, energy, and velocity through active experimentation. These topics are typically not studied until high school.

Vivarium Project
Topic: computers and ecology
Director(s): Kay
Institution: MIT and an elementary school in Los Angeles
Funding Source(s): Apple Computer
Age level: Elementary
Brief:

The Vivarium Project will allow students to understand natural wildlife ecology by building a computer-based synthetic model of its components and their interactions.

Voyage of the Mimi
Topic: mathematics and science education
Director(s): Gibbon
Institution: Bank Street College
Funding Source(s): DOE, NSF, CBS, Sony
Age level: 4th-8th grade (and above)
Brief:

The Voyage of the Mimi has been a major federal initiative to make research-informed multimedia materials--broadcast video, computer software, and print materials--for informal and classroom-based learning of mathematics and science in a narrative, dramatic format. The first season of shows, centering around whale research in the Atlantic, is in use throughout thousands of schools in the United States.

West

Topic: basic arithmetic skills
Director(s): Burton & Brown
Institution: Bolt, Beranek, Newman, Inc.
Funding Source(s): DoD
Age level: elementary school
Brief:

Embedded in a motivating, computer-game setting, West was an intelligent tutoring system that employed the "coaching" paradigm for teaching. West looked over the shoulder of the student as he/she played the computer game, and only judiciously interrupted to provide focused tutorial advice.

Word Learning Project
Topic: word meaning instruction
Director(s): Miller
Institution: Princeton University
Funding Source(s): DoD, Spencer Foundation
Age level: elementary school and up
Brief:

The authors are developing a system that goes significantly beyond a dictionary to help children acquire the meaning of words. In the context of a passage being read, a child can ask for alternative characterizations of the meaning of the words in the passage.

Word Problems Project
Director(s): Kaput
Institution: Harvard University Educational Technology Center
Funding Source(s): NIE, OERI, Apple
Age level: Elementary school
Brief:

The Word Problems Project has created and tested prototype software using linked multiplied representations--of picture icons of objects, paired numbers in a data table, a coordinate graph, and an algebraic equation--to help students learn about reasoning with intensive ("per," as in two candies per child) quantities. Through a concrete-to-abstract series of software environments, they "ramp" a child up to understanding graphic expressions of intensive quantities.